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J. Harlan Johnson, F.G.S.A., will study types of fossil coralline algae in museums abroad

Kazuo Kuroda will study the distribution of fluorine and chlorine in igneous rocks

J. Laurence Kulp, M.G.S.A., will establish a Strontium Isotope Method to measure age of sedimentary and metamorphic rocks

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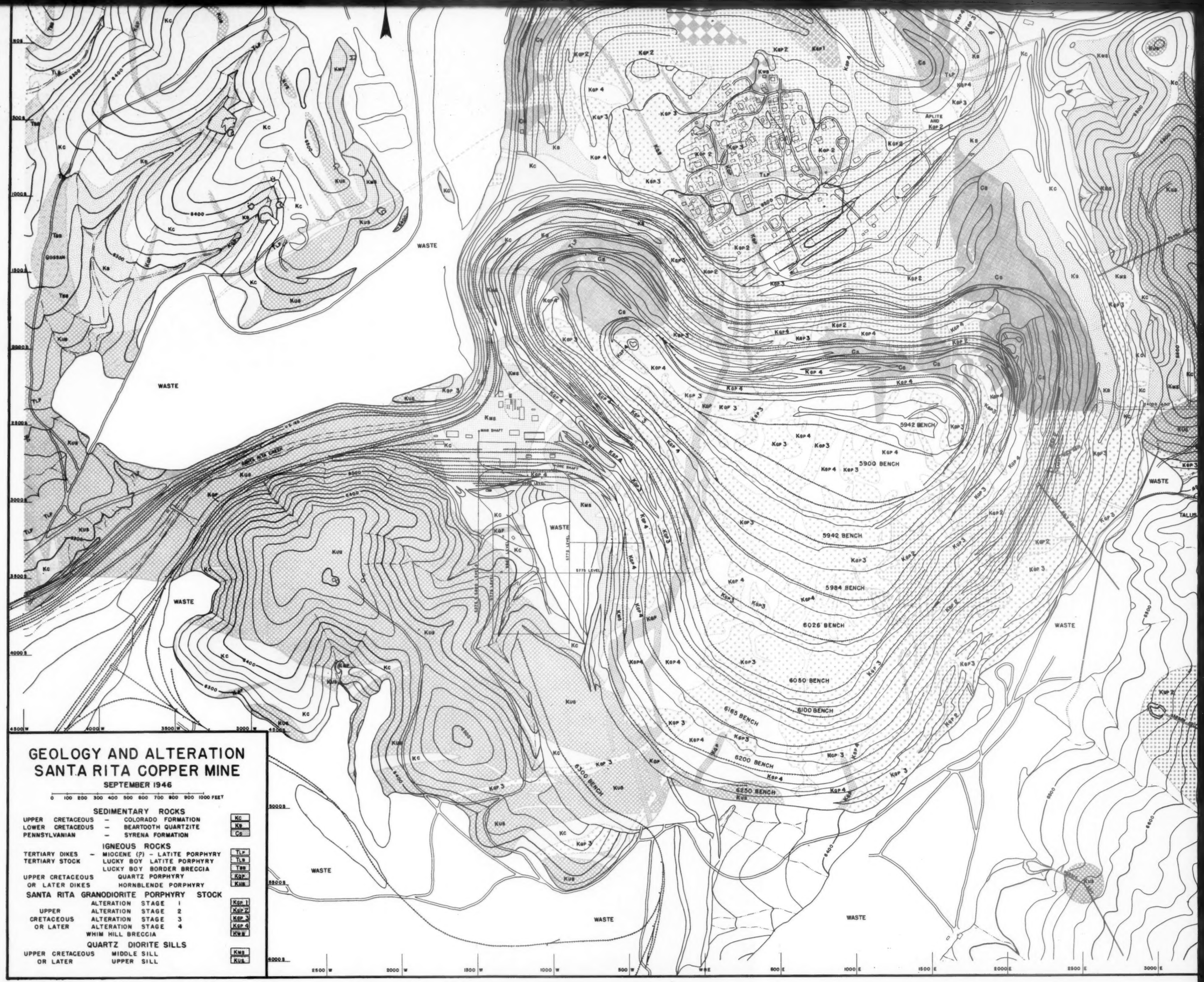
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GEOLOGY AND ALTERATION, SANTA RITA COPPER MINE

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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HYDROTHERMAL ALTERATION AT SANTA RITA, NEW MEXICO

By Paul F. Kerr, J. L. Kulp, C. Meade Patterson, and Robert J. Wright

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Abstract

The intrusives at Santa Rita and near-by Hanover differ widely in the extent of hydrothermal alteration. The Santa Rita intrusive is in many places highly kaolinized, sericitized, and silicified. The Hanover intrusive is to a large degree unaltered.

The study has centered around the hydrothermal alteration of the intrusive and to a lesser degree, alteration in dikes and sills in the vicinity. On the basis of field and laboratory criteria, four stages of alteration in the Santa Rita intrusive have been selected: (1) Areas of negligible alteration; (2) Areas of significant visible changes in the feldspars and ferro-magnesian minerals; (3) Areas of argillic alteration; and (4) Areas of sericitization and silicification. Comparison of ore distribution with alteration indicates that the highest concentration of copper is in general related to Stage 3. Secondary enrichment of chalcocite has contributed to the formation of ore in the argillic area, but some chalcocite may have been originally introduced with the argillic alteration of the Santa Rita intrusive. Comparable copper deposition has not been observed in the Hanover intrusive.

A considerable amount of oxidation occurs in some portions of the deposit, and areas near the surface have been extensively leached, but the change in alteration minerals previously formed appears minor.

Studies at Santa Rita indicate the utility of applying zones of alteration in field mapping, to outline areas of greater and lesser promise from the standpoint of mineralization. Data of considerable aid to the general projection of a drilling program are also developed.

Introduction

General Statement

The relationship of rock alteration to ore deposition in the Santa Rita area, New Mexico,

has revealed abundant alteration phenomena and has provided an exceptional opportunity to test a method of study still partially experimental.

Attention could be directed immediately to alteration phenomena since the principal geological features of the area had been previously described, and information was made accessible from the private files of mining companies.

The copper pits at Santa Rita are in effect a field exhibit displaying many miles of benches in altered rocks. The surrounding region provides abundant exposures in which the break down to clay minerals, sericite and quartz- plays an important role. The underground and surface mines permit observation of both alteration effects at the surface and mineralization at depth.

Work was started during the summer of 1946 and continued beyond the summer of 1947. Originally, it was proposed to concentrate on the surface exposures of dikes related to the underlying sphalerite ore bodies, but the scarcity of good exposures of these dikes led to a shift of focus to the altered Santa Rita intrusive and the accompanying sills.

Although field study was the most important part of the program, parallel laboratory investigations have included the examination of some 600 thin sections, the microscopic study of mineral fragments, x-ray diffraction analysis, and differential thermal analysis.

The conclusion that the general pattern of the ore accumulation at Santa Rita bears a direct relationship to the alteration is believed to be supported by the data. Numerous minor deviations from the general trend have been observed but evidence is strong that the zone of argillic alteration designated as Stage 3, together with near-by marginal areas, embraces what car lot assays have shown to be the principal ore-producing area.

Location

The mines studied lie in the southeastern corner of the Santa Rita quadrangle of the U. S. G. S., about 12 miles east of Silver City, New Mexico (Fig. 1). Hanover is about 1½ miles northwest and Vanadium approximately 2½ miles southwest of Santa Rita.

Three companies with large holdings have sponsored the project; Kennecott Copper, New Jersey Zinc, and American Smelting and Refining (Asarco). The terrain under their control has been available for study, and for all practical purposes has been considered adequate for the investigation.

A belt primarily important for zinc production extends from Hanover to Vanadium (Fig. 1). In order, these are the mines of the Empire Zinc Company at Hanover; the Oswaldo mine of Kennecott adjoining on the south; the Ivanhoe mine of Kennecott (now closed); and the Ground Hog mine of Asarco. The operations vary from surface pits on the Empire Zinc Company property to workings about 2000 feet below the surface in the Ground Hog mine.

Acknowledgments

The original project was the outgrowth of conversations with Mr. Anton Gray, chief geologist of Kennecott and much of the progress made is attributed to his continued interest. Mr. W. H. Loerpabel, manager of Asarco, made the facilities of his company available. Encouragement and valuable advice have been furnished by Mr. William Callahan, manager of the New Jersey Zinc Exploration Company. Mr. Kenneth Wilson, district geologist for Asarco, made a number of helpful suggestions.

All members of the local staffs were exceedingly cooperative. Mr. C. A. Schmidt, superintendent of the Empire Zinc Company and Mr. T. Alfred Snedden superintendent of Asarco Mr. Horace Moses, formerly general manager, and Mr. W. H. Goodrich, formerly general superintendent (now general manager) of the Chino Mines division of the Kennecott, made every facility of their organizations available.

Mr. Gerald J. Ballmer, now superintendent of the Chino Mines division of the Kennecott and formerly geologist for the company, made available an excellent suite of private reports and maps of the district, and liberally gave time to point out important geological features. Mr. George Ordonez, geologist with the exploration department of Kennecott, devoted several weeks to assist in the interpretation of field studies. The assistance of Mr. A. H. Morris, engineer for Kennecott, has been particularly important in view of the drilling operations conducted under his direction. Mr. K. A. Strand, geologist in charge of the Oswaldo

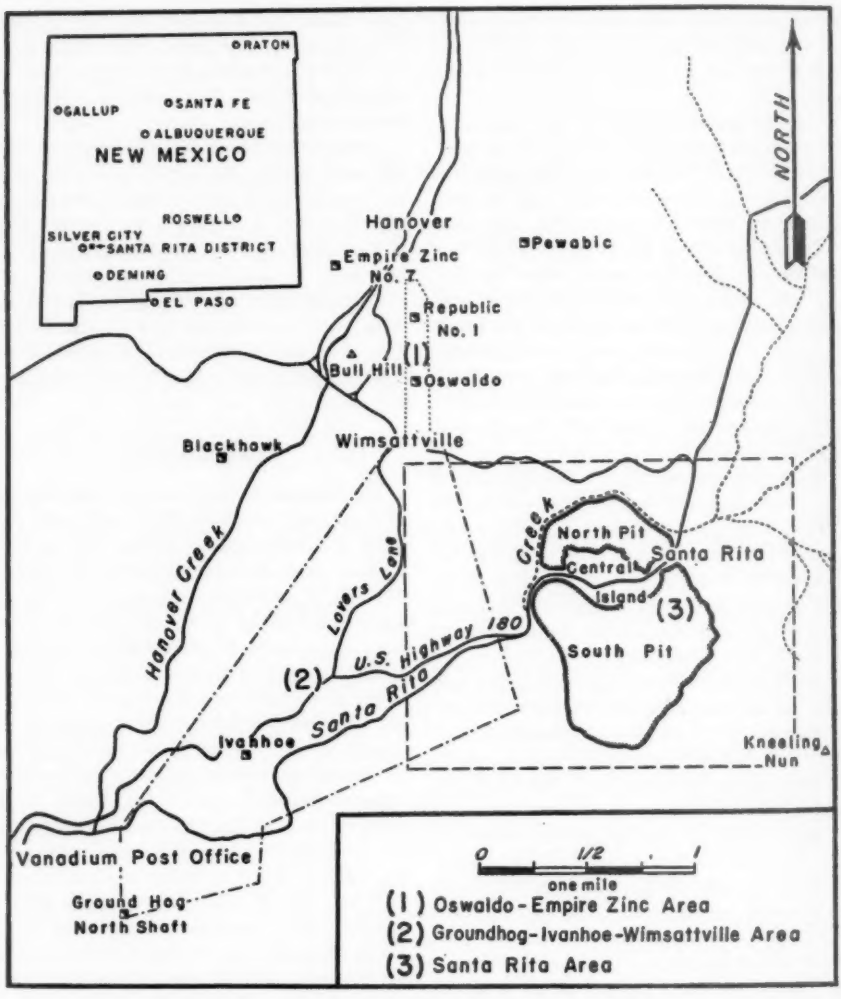

FIGURE 1.—INDEX MAP OF SANTA RITA AREA, NEW MEXICO

mine for Kennecott, called our attention to many geological features both underground and on the surface.

Mr. A. Hoagland and Mr. John Faick, geologists for the Empire Zinc Company, devoted much time and effort to the geological studies at the Hanover properties. Mr. James Pollock, and Mr. Thomas Mitcham, local geologists for Asarco, were most considerate in going over the alteration problems at the Ground Hog mine and in near-by territory. Previous studies by two men of wide experience in the district, Dr. Harrison Schmit, consulting geologist, and Dr. Samuel G. Lasky, district geologist for the U. S. Geological Survey, were most helpful both in the Hanover area and in the vicinity of the Ground Hog mine.

All members of the project express their keenest appreciation of the splendid cooperation of the staffs of the three companies. The

courtesy of the companies in agreeing in advance to make the results of the studies available for publication is also appreciated.

Nature of Alteration Studies

"Alteration study" is a term which has been applied to the investigation of clays and other fine mineral aggregates which often occur within or near mineral deposits. In the western United States such studies are found applicable, in and around the igneous intrusives, to deposits which yield copper, zinc, lead, silver, and gold. Studies (Kerr, 1947) which might be cited are known to have been carried on at Eureka, Utah[1]; Butte, Montana; Gilman, Colorado; Castle Dome, Arizona; San Manuel, Arizona; and Boulder, Colorado.

Alteration minerals are for the most part fine-grained and must be examined by more than ordinary mineralogical techniques. At Santa Rita, the most significant after the common clay minerals are, sericite, jarosite, alunite, limonite, fine pyrite, chlorite carbonate, and quartz.

Although current interest in alteration, from the standpoint of ore deposition, was largely initiated by the report on the Boulder, Colorado, tungsten deposits by Lovering (1941), the technique is probably more useful in areas yielding copper, lead, and zinc. In such places the zones of alteration are more widespread and afford better opportunities for observation. Judging from the exposures at Santa Rita and from the few published descriptions of other deposits, the porphyry copper deposits may provide some of the best sites to study alteration, particularly where mining is carried on in open pits.

Alteration has been long recognized as accompanying certain phases of ore deposition, but the study has received much benefit of late from the fundamental studies on the clay minerals.

Previous Geological Work

The history of mining at Santa Rita dates from the early days when ore was transported by pack train to Chihuahua and Mexico City.

[1] A report on the East Tintic District has been published since this was written (Lovering, 1949).

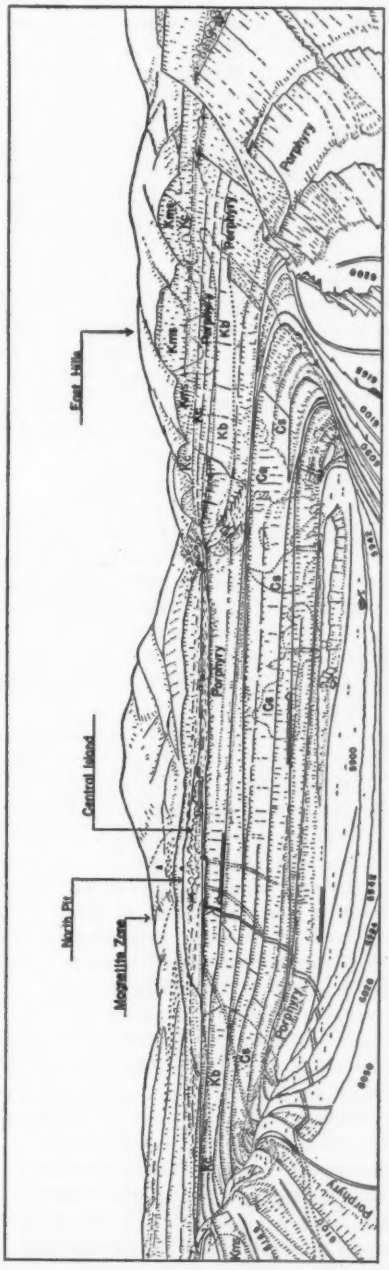

FIGURE 2.—SOUTH PIT, SANTA RITA, NEW MEXICO

The Central mining district, which includes the area, was organized in 1860.

Previous studies include Paige (1909, 1912, 1916, 1933, 1934), Spencer and Paige (1935), Schmitt (1933, 1935, 1939A, 1939b, 1942), and Lasky, (1930, 1936a, 1936b, 1942). Unpublished geologic maps of a part of the area have been made by G. J. Ballmer, James Pollock, George Ordonez, and Harrison Schmitt. The latter cover substantial portions in great detail.

Published geologic maps constitute an excellent framework upon which more detailed studies may be constructed. However, many details and a few major features have been further developed in the present study, and observation of the areas of alteration has occasionally resulted in re-interpretation of the geologic pattern.

General Geological Features

Paleozoic and Mesozoic rocks are exposed where Tertiary lavas, tuffs, and sediments have been removed by erosion. The Tertiary cover remains along the southern margin of the area and forms a dissected plateau with, rugged escarpments rising over 1,000 feet above the surrounding terrain.

Sedimentary formations, Mississippian through Cretaceous in age, have been intruded by Cretaceous quartz diorite sills arched and cut by two granodiorite porphyry stocks, probably Laramide. One comparatively unaltered stock forms an elliptical mass 2½ miles long near Hanover, while another highly altered but smaller stock crops out at Santa Rita. The former is essentially unmineralized; the latter is copper bearing and embraces a considerable part of the Santa Rita ore body.

Grandiorite porphyry dikes cut the surrounding sedimentary rocks, sills, and in some cases even the stocks. Tertiary latite dikes cut the entire sequence of older rocks. Zinc and iron deposits have been found along the margins of the stocks and along certain of the dikes.

Ore deposits consist of: disseminated copper mineralization as in the granodiorite porphyry stock at Santa Rita; contact metamorphic zinc and iron deposits developed by replacement of limestone adjacent to the Hanover stock, the Santa Rita stock or associated dikes; lead-zinc fissure deposits and zinc replacement bodies near granodiorite porphyry dikes as at the Ground Hog and Ivanhoe mines.

A diagram of the South Pit at Santa Rita (Fig. 2) shows the west, north, and east sides of the pit with the central island. The distant magnetite zone is aligned approximately with the northern lobe of the Santa Rita stock.

Recent operations in the pit have been conducted chiefly in the zone of highly altered biotite granodiorite porphyry (Pl. 1), the principal ore bodies lying in the argillic phase. On the north wall of the pit are isolated sedimentary remnants, believed to belong to the Syrena formation, caught in the upper part of the intrusive. Later dikes cut across the pit on the left of the view, while on the extreme left, contacts with the Syrena formation (Cs), Beartooth quartzite (Kb), Colorado formation (Kc), and Middle sill (Kms) may be seen.

East Hill is underlain by sedimentary rocks and sills invaded by porphyry. The sedimentary rocks include the Syrena formation (Cs), the Beartooth quartzite (Kb), and the Colorado formation (Kc). The Middle sill forms part of the eastern crest of the artificial escarpment along the rim of the pit. East Hill is underlain chiefly by the Upper Sill although the latter is not indicated in the diagram.

The principal area of alteration studied embraces the granodiorite stock in the vicinity of Santa Rita (Fig. 1). From here observations extended southwest to the Ground Hog mine and northwest to the Hanover stock.

Most of the boundaries shown follow the maps of Spencer and Paige (1935, Pl. 1) or Lasky (1936a, Pl. 1). Previous mapping has been modified in the vicinity of the Santa Rita stock and around the Lucky Boy intrusive to the west (Fig. 3).

Extensive hydrothermal alteration occurs within and adjacent to the Santa Rita stock, but the Hanover stock is essentially unaltered. Between the Hanover stock and the Ground Hog mine, sericitic and argillic alteration areas are confined to dikes, or portions of sills near dikes or faults. Where hydrothermal alteration is intensive, the epidotization connected with contact metamorphism is largely obscured.

In the center of the north wall of the North Pit (Fig. 4) lie exposures of the Whim Hill breccia, which forms a core in the Santa Rita

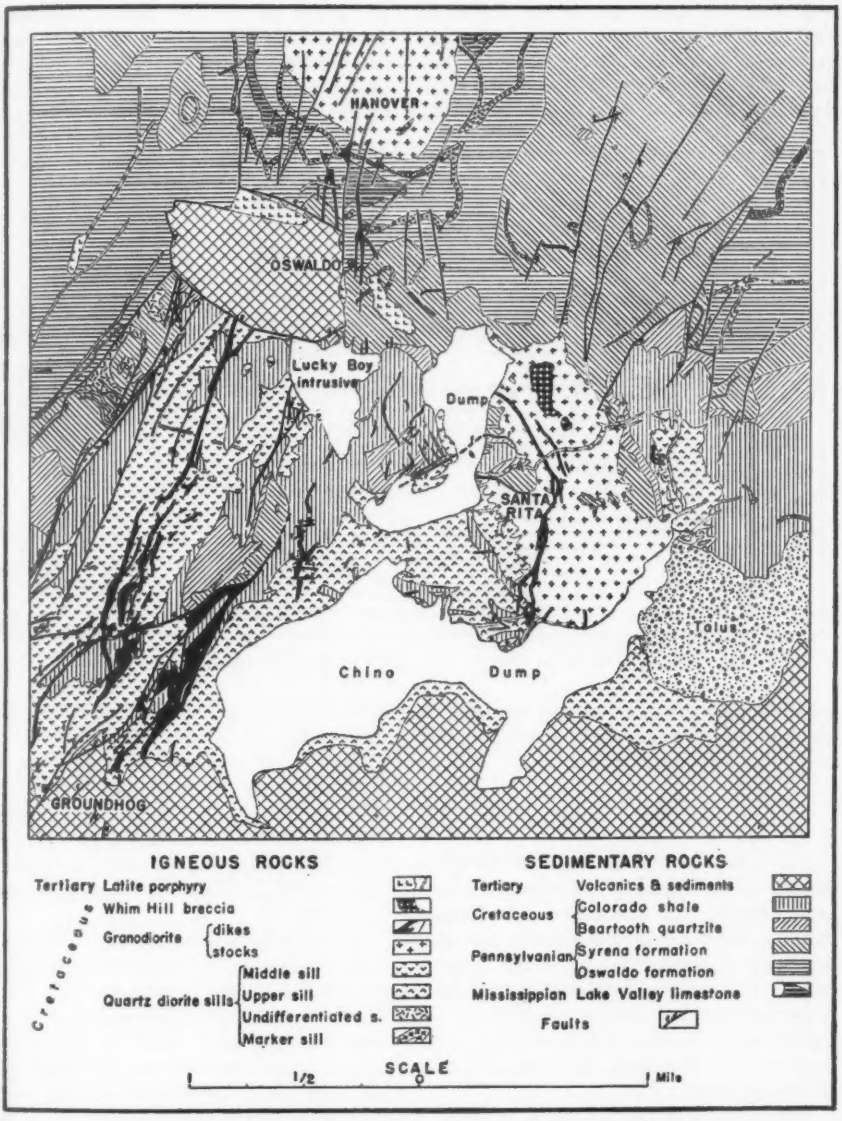

FIGURE 3.—GENERAL GEOLOGY, SANTA RITA AREA, NEW MEXICO

stock. On either side are zones of alteration representing progressively altered biotite granodiorite porphyry. At the extreme right is the Syrena formation invaded by biotite granodiorite porphyry subsequently altered to an argillic phase showing the greatest concentration of clay minerals.

SEDIMENTARY ROCKS

General Description

Sedimentary rocks outcropping in the area (Fig. 5) range from Mississippian through Tertiary. However, only the pre-Tertiary formations were subjected to the intense hydrother-

mal alteration accompanying ore deposition (Fig. 3). Older beds crop out to the north along the margin of the Hanover stock, where they have been arched and brought to the surface. The same beds have been cut in deep drill holes of the Empire Zinc Company, immediately south of the Hanover stock, and in the 700-foot water well of Kennecott.

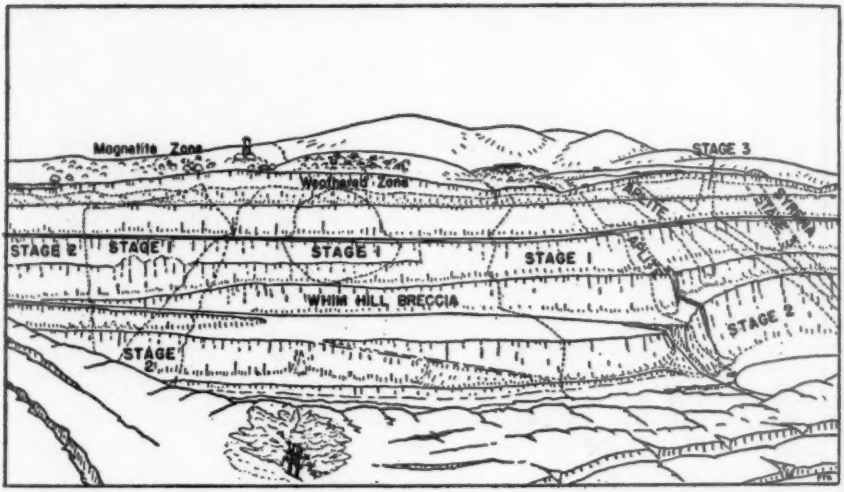

FIGURE 4.—NORTH PIT, SANTA RITA, NEW MEXICO

Unexposed Rocks

The Cambrian Bliss sandstone is the oldest member of the Paleozoic sequence in southern New Mexico, first described by Richardson (1904, p. 27) in the Bliss Mountains, 100 miles southeast of Santa Rita. It consists of gray, brown, and maroon conglomerate and sandstone. Glauconitic layers are common, and the upper portion contains thin layers of dolomite and dolomitic limestone. At Fierro, the Bliss is 186 feet thick.

Ordovician and Silurian rocks comprise a series of limestones and dolomites which Richardson (1908 p. 476) separated on the basis of fossil assemblages into the El Paso and Montoya limestones, of Ordovician age, and the Silurian Fusselman limestone. This sequence is locally designated the "lower limestones" in contrast to the Carboniferous limestones. The El Paso is dolomitic in part, predominately thin-bedded and arenaceous at the base, becoming more massive and cherty toward the top. At Fierro, it is the chief host rock for the contact metamorphic magnetite bodies; there the formation is 216 feet thick. The Montoya is a massive white to gray cherty dolomite with a 10-foot basal sandstone member, 427 feet thick at Fierro. The Fusselman is a massive dolomitic cherty limestone, so similar to the underlying Montoya that it can be distinguished only on fossil evidence. Its thickness at Fierro is 40 feet.

Above the Ordovician-Silurian limestones and dolomites lies the Devonian Percha shale, first described by Gordon (1907, p. 92) from Percha Creek west of Kingston. The lower portion consists of black fissle shale grading upward through shaly limestone into the limestone of the Lake Valley formation. Included in the Percha are several quartz diorite sills of considerable thickness. Exclusive of sills the formation varies from 100 to 300 feet thick. At Hanover, diamond drill cores from this shale show various stages of epidotization from a typical shale texture to complete recrystallization.

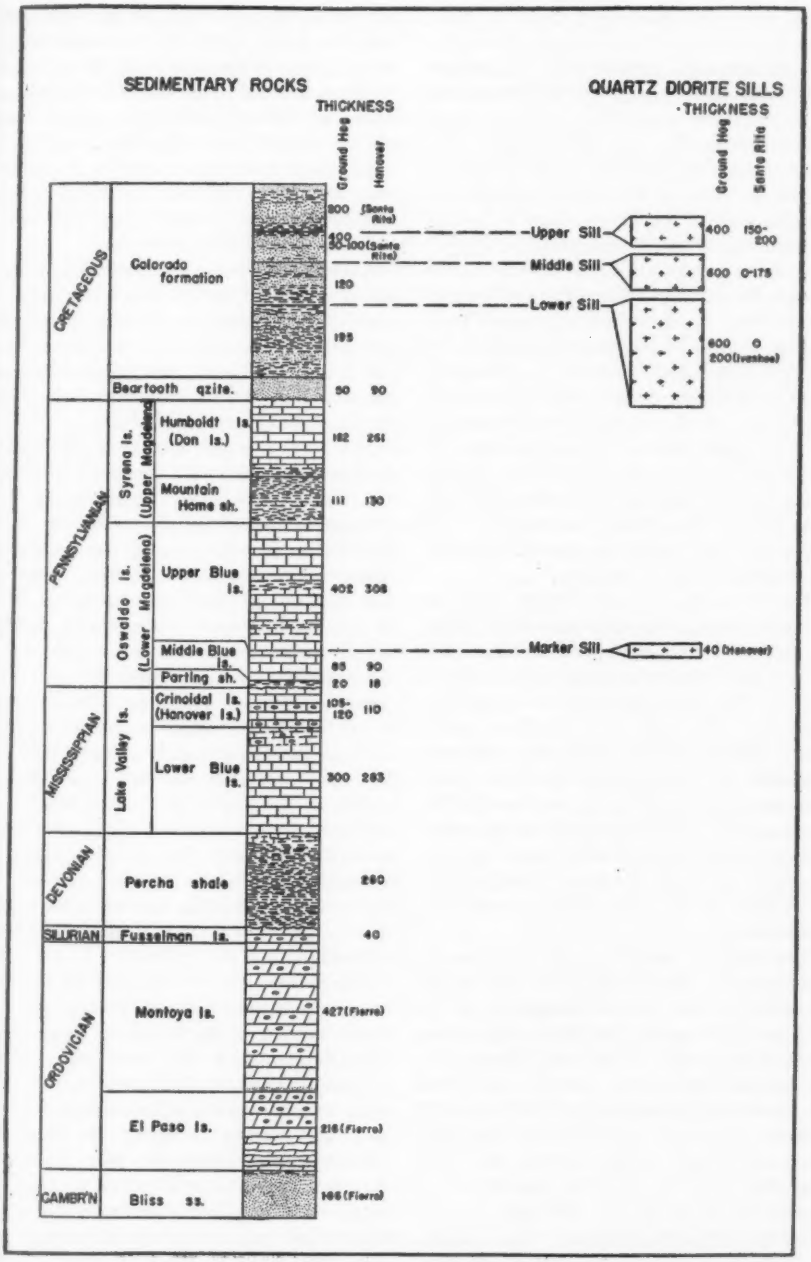

FIGURE 5.—GEOLOGIC SECTION, SANTA RITA AREA

Exposed Rocks

In the area under investigation, sedimentary rocks outcropping include Carboniferous limestones and shales overlain by Cretaceous shales and sandstones. The lower Mississippian beds, oldest in the area, crop out along the axis of the asymmetrical anticline which parallels the southern edge of the Hanover stock. A fairly complete sequence of younger units through the upper Pennsylvanian is exposed on the moderately inclined southern flank of the anticline between the Empire Zinc Republic No. 1 shaft and Wimsattville. South of this area of comparatively simple structure, Cretaceous rocks predominate except where older rocks are brought to the surface around the rim of the Santa Rita stock or along fault zones.

Recognition of formations in the vicinity of the Hanover and Santa Rita stocks is difficult, because of extensive metamorphism and alteration plus local structural complexities combined with lack of outcrops.

The Mississippian Lake Valley limestone includes the horizon in which most of the Hanover zinc ores have been formed. Its type locality is in the Lake Valley mining district (Cope 1882, p. 214). The Lake Valley is divided into the Lower Blue limestone, which is usually barren, and the overlying Crinoidal or Hanover limestone, the common host rock. The Lower Blue limestone is dark-gray, medium-bedded, non-magnesian and characterized by thin shale beds and dark chert nodules toward the top. Locally it contains beds of pure-white limestone in which small ore bodies may be formed by replacement.

The Crinoidal limestone appears at the surface only along the anticlinal axis south of the Hanover intrusive. On the south limb of the anticline it disappears beneath younger rocks, inclined moderately to the south. Workings in the southern end of the Oswaldo mine follow the formation to a depth of 600 feet below the surface. It extends beyond the Ground Hog mine and comes to the surface near Lone Mountain west of Hurley. The maximum depth attained is on the order of 2500 feet.

Where not metamorphosed, the Crinoidal is white coarse-grained massive calcite characterized by lenses and nodules of white chert. According to Schmitt (1939, p. 801) chert is the only impurity. Crinoid stems are the main constituent but in the Hanover area the primary texture of the rock is usually destroyed by recrystallization related to the deformation during intrusion of the Hanover stock. Because of its physical and chemical nature, the Crinoidal is markedly susceptible to replacement and forms the main ore horizon in the Empire Zinc and Oswaldo mines. The formation averages about 110 feet thick.

Above the Lake Valley limestones lie limestones and shales in the Magdalena group of lower Pennsylvanian age. Locally the Magdalena is divided into two units defined by Spencer and Paige (1935, p. 23), the Oswaldo formation below and the Syrena formation above. Each formation has several subdivisions.

The basal member of the Oswaldo is the Parting shale which rests unconformably upon the Crinoidal limestone. It is arenaceous, rich in plant remains, and about 20 feet thick. The Middle Blue immediately above is a medium-gray non-magnesian limestone about 90 feet thick which resembles the Lower Blue. It contains thin beds of pure-white limestone which are sometimes replaced to form small low-grade zinc ore bodies. Black chert and shaly layers are common. The Upper Blue limestone at the top of the Oswaldo is gray non-magnesian, and massive, but shaly in part, about 400 feet thick. Lithologically the Upper Blue is similar to the Middle Blue, from which it is separated by a Cretaceous quartz diorite sill about 40 feet thick. The sill is consistent in stratigraphic position and serves as a convenient unit in separating the two similar limestones. It is known as the Marker sill or Hanover sill.

The Syrena formation has been divided into two mapping units (Schmitt, 1935, p. 88). The lower member is the Mountain Home shale, 110–130 feet thick. The remainder consists of some 250 feet of alternating limestone and shale with several discontinuous quartz diorite sills. This portion is named the Humboldt limestone (also called the Don limestone). Where exposed in the Santa Rita pit along the margin of the granodiorite stock, the upper Syrena has been extensively metamorphosed. The entire formation has been highly silicified and chloritized, and more calcareous beds must have been replaced by magnetite and pyrite.

Magnetite replacement bodies in the Syrena have been prospected on the hill slope immediately north of the Ivanhoe shaft.

The limestone members of the Syrena formation weather readily and exposures are sparse so that it is difficult to map formational contacts.

Red sandstones, sandy shales, and limestones overlie the Syrena formation at certain localities north and east of Santa Rita. Spencer and Paige (1935, p. 26) correlated the rocks with the Permian Abo sandstone. According to Lasky (1936a, p. 19), Abo is lacking in the Bayard area west of Santa Rita, Cretaceous rocks there lying directly on the Syrena formation. A body of highly silicified and chloritized rock containing magnetite and pyrite underlies the Cretaceous along the east wall of the South Pit at Santa Rita. The beds were considered Abo by Spencer and Paige. In this work, however, the intense alteration made it impossible to distinguish these rocks from the metamorphosed Syrena. In view of this and the uncertainty as to identity, it was decided to consider these beds part of the Syrena.

Cretaceous rocks include a considerable thickness of shales, quartzites, and sandstones. The basal Beartooth quartzite was defined by Paige (1916, p. 5) from Beartooth Creek north of Fort Bayard. The quartzite is overlain by shales of the Colorado formation. The Beartooth, which lies unconformably upon the Syrena (or Abo), consists of light-colored massive conglomerate, vitreous quartzite, and sand stone with a few shaly layers. It varies from 50 to 120 feet thick. The line of outcrop is marked by large jointed blocks commonly without trace of bedding so that it is impossible to determine the attitude of the beds. The Beartooth is overlain by the Colorado formation, a group of variegated shales and sandstones. Included in the formation are three quartz diorite sills of Cretaceous age. Lasky (1936 a, b), in the Bayard area, split the Colorado into a lower shale member and an upper sandstone member. Herein interest has centered primarily in the sills rather than the enclosing rocks, so this distinction has not been followed. The top of the Colorado is either the present erosion surface or an older erosion surface upon which the Tertiary volcanics rest. If the upper part of the Colorado as exposed east of the Santa Rita pit is correlated with the lower portion exposed in the Ground Hog mine, a total thickness of 500 feet is obtained for sedimentary rocks exclusive of sills.

IGNEOUS ROCKS

Quartz Diorite Sills

Quartz diorite sills of Upper Cretaceous age occur within the Percha shale, the Oswaldo limestone, the Syrena formation, and the Colorado formation. The Marker sill, lying between the Middle Blue limestone and the Upper Blue limestone, has already been described. The three sills in the Colorado formation (Fig. 6) are the host rocks for ore in the upper levels of the Ground Hog mine. However, later developments indicate that the lower sill invades earlier strata. At Santa Rita, two of the sills in the Colorado are highly altered and in places mineralized to form commercial ore.

Because of mineralization and attendant alteration, the sills of the Colorado formation have received special study. The upper and Lower sills of the Colorado formation are similar in composition and texture but the Middle sill differs in texture. From field relations, Lasky (1936, p. 26) has established that the quartz diorite of the Middle sill is younger than quartz diorite of the Upper and Lower sills. The rocks are so similar petrographically that the age difference is not great.

The Upper sill (Pl. 2, figs 1, 2) crops out between the Ivanhoe-Lovers Lane fault and the South Pit. On the west (upthrown) side of the fault, the Upper sill has been removed by erosion, and the Middle sill is exposed at the surface. At the Ground Hog mine the Upper sill is present in the hanging wall of the Ivanhoe-Lovers Lane fault and is over 400 feet thick. The upper contact has been eroded so the original thickness cannot be measured. Diamond drilling east of the South Pit indicates that the Upper sill there varies from 60 to 200 feet thick. In general it thins eastward.

The Middle sill (Pl. 3, figs. 1, 2) is exposed over a large area west of the Ivanhoe-Lovers Lane fault. At the Ground Hog mine, 200 feet of sill are preserved in the footwall of the Ivanhoe-Lovers Lane fault. East of the fault, the Middle sill is below the surface, cut by work-

ings of the Ground Hog mine and by open pit operations and diamond drill holes at Santa Rita. It thins from over 400 feet thick at the Ground Hog mine to 175 feet at the east edge of the South Pit, and disappears east of the Pit.

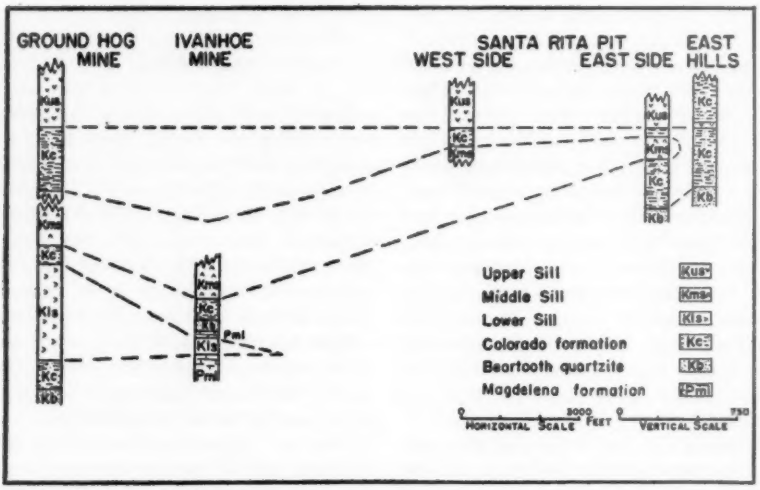

FIGURE 6.—SILL DEVELOPMENT IN THE COLORADO FORMATION

The Lower sill (pl. 2, figs. 3, 4), known largely from workings in the Ground Hog and Ivanhoe mines, is 600 feet thick at the Ground Hog mine, and lies 195 feet above the base of the Colorado formation; thins rapidly eastward, about 200 feet at the Ivanhoe mine; and disappears before reaching Santa Rita.

In general, the three sills in the Colorado formation thin progressively from the Ground Hog mine eastward toward Santa Rita (Fig. 6). Thinning is accompanied by convergence of the intervals of Colorado formation between the sills. The Middle sill persists as far as Santa Rita but disappears under the hills a short distance east of the South Pit. The Upper sill is continuous throughout the area but it thins from 400 feet at the Ground Hog mine to 60 feet at Santa Rita.

The Upper sill is dark green and porphyritic (Pl. 2, figs. 1, 2). Feldspar forms the most abundant phenocrysts and makes up about 40 per cent of the rock. Andesine is predominant, with minor quantities of orthoclase and variable amounts of introduced albite. The albite may be relatively fresh, whereas the andesine is usually clouded with sericite or replaced by epidote. Quartz phenocrysts up to 2.5 mm. in diameter are irregularly distributed. On hand specimens these may appear as doubly terminated frosted crystals, which aid in field recognition of the rock. Biotite and hornblende are altered to rectangular masses of epidote and chlorite. No thin sections showed unaltered ferromagnesian minerals.

Magnetite is usually present as a primary accessory mineral; apatite is less common. The ground mass consists of a mosaic of quartz grains about .01 mm. in diameter, and is usually clouded by such alteration minerals as chlorite, epidote, calcite, sericite, or limonite.

The Middle sill is dull green to buff. Phenocrysts (Pl. 3, figs. 1, 2) are smaller and more numerous than in the Upper sill, yielding an equigranular appearance. The component minerals are small and, in many cases, obscured by alteration. Small andesine laths make up about half of the rock, and prismatic crystals altered to epidote and chlorite are common. Quartz and biotite phenocrysts are lacking while magnetite is sparse and erratic in distribution. The groundmass consists of fine-grained quartz and scattered alteration min-

erals. The sill can be distinguished from the adjacent sills by (1) finer-grained, more equigranular texture, (2) absence of quartz phenocrysts, (3) absence of biotite phenocrysts. The Middle sill is further characterized in thin section by a general lack of magnetite and characterized in thin section by a general lack of magnetite and apatite.

Both the Middle and Upper sills are in places sheeted parallel to the contact with enclosing rocks as shown in exposures of the Upper sill in the valley across Whitewater Creek from the Kennecott precipitating plant and near the base of the Middle sill southwest of the Lucky Boy intrusive.

Hanover Intrusive

The Hanover and Santa Rita intrusives are granodiorite porphyry, being similar both petrographically and in general relations, although the alteration and mineralization differ markedly.

The granodiorite porphyry forming the Hanover stock is a likely equivalent of the Santa Rita granodiorite porphyry. The proximity of the two known masses, the similarity of regional structure, the occurrence in both of aplites, the magnetite zones bordering both intrusives, the similarity of texture and mineral content, all point to contemporaneous invasion from the same magma. A deep-seated connection between the two igneous masses may exist and the intrusives of Hanover and Santa Rita are likely cupolas of a common deep-seated batholith.

The granodiorite porphyry of the Hanover stock forms a body of relatively unaltered rock in a region of intense mineralization. The lack of hydrothermal alteration in the Hanover intrusive is emphasized by the apparent absence of pyrite and only the slightest development of sericite, chlorite, and argillic (Lovering, 1941) alteration.

Even the grandiorite porphyry of the least altered stage found in the North Pit at Santa Rita has undergone more alteration than may be observed in the porphyry at Hanover. Thus the Hanover intrusive by inference indicates the original character of the Santa Rita rock prior to alteration.

The Hanover granodiorite porphyry is generally coarsely crystalline, showing prominent phenocrysts of plagioclase, hornblende, and biotite, ranging from porphyritic to granular (Pl. 3, fig. 4). The ground mass which makes up 40–70 per cent of the rock is dense and

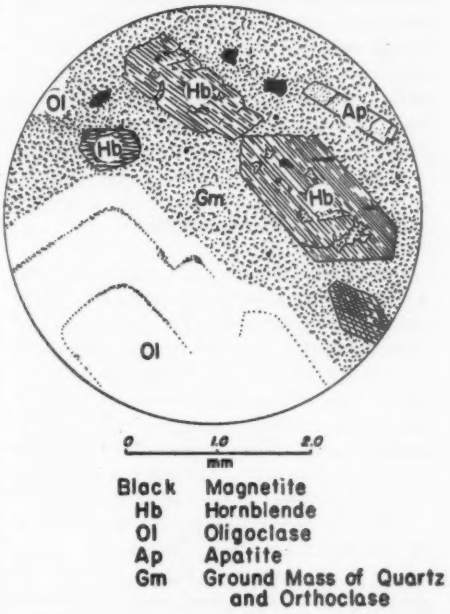

FIGURE 7.—HANOVER GRANODIORITE PORPHYRY

gray to buff. In places it increases in amount and decreases in grain size to enhance the porphyritic appearance (Fig. 7). Lustrous oligoclase phenocrysts measure 0.5–10 mm. long and show zoning as well as albite and pericline twinning. The dull-white and gray alteration of the feldspar phenocrysts at Santa Rita is missing. Hornblende (Fig. 7) appears prominently in slender dark-green pleochroic crystals measuring as much as 7.0 mm. long. Biotite phenocrysts occur as barrel-shaped crystals up to 5.0 mm. across. Some chlorite development occurs along cleavage traces.

The estimated abundance of the rock-forming minerals is: feldspar, 70 per cent; hornblende, 10–20 per cent; quartz, 10–15 per cent; biotite, 5 per cent. Accessory minerals include diamond-shaped euhedral sphene, apatite, and zircon. Magnetite, common as irregular masses and grains of 0.1 to 0.6 mm. diameter, is usually

found within or near hornblende prisms or along the edges of sphene crystals. Sulfide mineralization is noticeably absent. In porphyritic granodiorite, phenocrysts of plagioclase, hornblende, and biotite occur in a granular ground mass of quartz and orthoclase.

Oligoclase and hornblende were the earliest silicate minerals to crystallize in the Hanover stock. Quartz and orthoclase were later (Pl. 3, fig. 4). Biotite may belong in this second group. Magnetite appears to be the latest of the common mineral constituents.

Santa Rita Intrusive

Description.—The Santa Rita intrusive forms a rounded body about a mile across and is best exposed in the copper pits. The stock is apically truncated and is bounded by metamorphosed sedimentary rocks that have been partially removed by recent mining operations. (Fig. 2; Pl. 1). The alteration study of the Santa Rita stock presumes a single intrusive mass of biotite granodiorite porphyry. The original characteristics are suggested by the least altered portion.

The granodiorite porphyry has been referred to as quartz porphyry (Brinsmade, 1908), quartz diorite porphyry (Sully, 1909), diorite porphyry (Ball, 1910), and quartz monzonite porphyry (Lindgren, Gaton and Gordon, 1910); Paige, 1912, 1916; Rickard, 1923). More recently the rock has been described as granodiorite (Landon, 1929) and granodiorite porphyry (Spencer and Paige, 1935) although S. F. Emmons (1899) regarded the igneous rock of Santa Rita as being "probably granodiorite."

Landon (1929) has estimated the mode of the intrusive rock as orthoclase, 12%; quartz, 15%; oligoclase, 63%; hornblende, 8%; and acessories 2%. The high percentage of hornblende and the absence of biotite are more characteristic of the near-by Hanover stock and do not correspond to the many sections studied in this investigation.

Spencer and Paige (1935, p. 36), describing the porphyry from the exposures in the North Pit, observe: "A careful estimate indicates that the proportions of andesine and orthoclase are respectively about 40 to 16 per cent, so that the stock falls under the classification of granodiorite rather than quartz monzonite."

The Santa Rita granodiorite porphyry contains evenly distributed phenocrysts in a dense gray groundmass although, like the Hanover intrusive, this porphyry also shows some variations in texture. Lustrous, striated green-gray feldspar phenocrysts are common, while coarse hornblende and quartz occasionally occur.

The plagioclase phenocrysts lie between calcic oligoclase and sodic andesine. Zoning and albite twinning are apparent in all phenocrysts and some show both albite and pericline twinning. The crystals have been corroded and embayed by the groundmass quartz and orthoclase of late crystallization.

The biotite flakes are generally about 2 mm. across. Hornblende phenocrysts with pale- to olive-green pleochroism occur infrequently. Although ordinarily the most characteristic mineral, occasionally the porphyry shows little biotite.

The groundmass consists of equigranular, interlocking grains of quartz and slightly sericitized orthoclase. The quartz and orthoclase were probably contemporaneous although some quartz is later. Generally the feldspar in the groundmass is fresher than the phenocryst feldspar. Interstitial magnetite, pyrite, and limonite occur throughout the groundmass. Accessory sphene, apatite, zircon, and rutile are found. Magnetite is a common constituent and occurs as irregular or skeletal grains 0.3–1.0 mm. in diameter.

The Santa Rita prophyry is distinguished most sharply from the Hanover prophyry by the dominance of biotite in the former and hornblende in the latter.

Sequence of Crystallization.—The texture of the Santa Rita biotite granodiorite porphyry points toward: 1. An earlier stage of crystallization of the euhedral phenocrysts. 2. A later stage characterized by the solidification of residual liquors to form the interstitial mass of orthoclase, quartz, and biotite.

Phenocrysts of hornblende were among the earliest to crystallize. Abundant iron-rich biotite followed and in places forms reaction rims about the earlier amphibole. Contemporaneous with the crystallization of the hornblende and biotite, plagioclase feldspar crystallized as zoned crystals with cores of andesite becoming increasingly sodic outwards to the oligoclase margins. Quartz phenocrysts were probably the latest to form.

As the early phenocrysts were transported in the solid phase through the residual liquors of the congealing stock, some suffered corrosion and resorption. Quartz was exceptionally vulnerable being everywhere attacked by residual solutions believed to have been highly alkaline. Hornblende phenocrysts likewise were shredded and embayed. Biotite and plagioclase, prior to the complete solidification of the granodiorite, retained and extended their boundaries at the expense of the ground mass liquors to form the largest crystals among the early minerals.

The minor accessories sphene, apatite, zircon, and rutile were generally early, crystallizing with the phenocrysts. Magnetite followed, with the crystallization of the ground mass and still later in the post-magmatic stage of deuteric and high-temperature mineralization. Some apatite embedded in quartz may likewise be post-magmatic.

Periods of mineralization.—Mineralizing solutions were guided in their movement upward through the granodiorite porphyry and the intruded formations by porosity due to hydrothermal action and intense fracturing. The first wave of metallic deposition formed magnetite in irregular grains or small crystals. The Whim Hill breccia was cemented by magnetite and orthoclase. Massive magnetite veins also cut through the contact phases bordering the stock. Although magnetite was originally distributed throughout the stock as disseminated, interstitial grains in the granodiorite porphyry, most of the iron-rich solutions rose later through the border phases of the intrusive. Magnetite, pyrite and in a few places chalcopyrite were formed by replacement in the calcareous rocks of the nearby Syrena Formation.

The magnetite-precipitating solutions subsided as a period of aplitic injection followed. The residual felsic solutions filled prominent parallel fissures in the granodiorite porphyry.

The next surge of mineralizers introduced pyrite and small amounts of molybdenite. Pyrite is ubiquitous in the granodiorite porphyry and replaces earlier magnetite. Pyrite marginal to magnetite grains is rarely found in the fresh granodiorite porphyry. However, pyrite and magnetite appear mutally exclusive in the altered rock. The later pyrite frequently cuts through the veins and beds replaced by magnetite in the Syrena formation.

The quartz porphyry dikes of the Santa Rita and Hanover districts were injected at about this stage and appear to separate the primary mineralization at Santa Rita into an early and late epoch. The quartz-bearing granodiorite dikes cut the pre-mineral hornblende granodiorite porphyry dikes which lie west and northwest in the Hanover-Ground Hog zone. In the Santa Rita intrusive, a prominent quartz porphyry dike has been emplaced along north to northeasterly fissures. Other quartz porphyry dikes found in outcrops of the Central Island have similar alignment.

Quartz veins were formed throughout an extended period of mineralization. Having started to form prior to the injection of the quartz porphyry dikes, the pyrite continued until the close of primary mineralization.

Veins and disseminated grains of chalcocite occur most abundantly in the altered porphyry, and the mineral is later than pyrite at Santa Rita. It is believed that the chalcocite may belong to a late phase of hypogene mineralization as well as being a participant in supergene enrichment.

Whim Hill Breccia

Description.—A cemented fragmental rock known locally as the Whim Hill breccia (Landon, 1929) forms two areas of exposure in the northern part of the Santa Rita stock (Pl. 1). The larger comprises an area of over 40,000 square feet and forms a somewhat elongate mass in the central part of the North Pit where it encloses a rounded block of biotite granodiorite porphyry. The second body which is much smaller is found on the northern edge of the Central Island between the North and South Pits. The breccia masses are bounded by slightly to moderately altered biotite granodiorite porphyry and occupy the core of the Santa Rita stock.

The breccia forms a mass of angular blocks cemented by a matrix rich in magnetite (Fig. 8; Pl. 5, fig. 1). The fragments represent a number of rock types known to occur in the stratigraphic section (although definite sill rock was not identified). Broken pieces of biotite granodiorite porphyry predominate. Angular and rounded fragments of indurated shales and quartzites which probably came from the Beartooth and

Colorado formations may be seen. The fragments of biotite granodiorite porphyry are somewhat altered but not highly, hence the breccia may be considered as having been

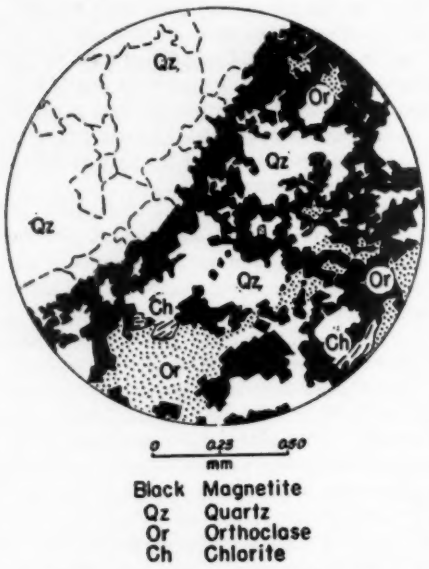

FIGURE 8.—WHIM HILL BRECCIA. Boundary between quartz fragment and magnetite matrix.

formed subsequent to some of the earliest hydrothermal alteration of the surrounding granodiorite porphyry.

On the whole, the breccia is compact and firmly cemented, but small miarolitic cavities appear occasionally within the matrix. One cavity about an inch across was lined with euhedral crystals of magnetite. Veins of aplite have been found cutting the breccia.

Fragments.—Generally fragments of the breccia range from microscopic dimensions to angular blocks 9–12 inches on a side, but occasional well-rounded or even spherical fragments indicate considerable milling after brecciation. Close observations of the matrix show angular fragments .5–2.0 mm. in diameter.

The biotite granodiorite fragments vary from nearly equigranular to coarsely porphyritic. Phenocrysts of oligoclase, hornblende, biotite, and less commonly quartz occur in variable ground masses of orthoclase, rare oligoclase, quartz, biotite, and chlorite. Accessories include magnetite, apatite, rutile, and zircon. The phenocrysts of oligoclase may be fresh or altered to such a degree that the prominent plagioclase twinning is obscured. The hornblende, found only as unreplaced cores and amphibole outlines, is replaced by chlorite and laths of biotite. The phenocrysts of original biotite are but slightly altered to chlorite. In thin sections some varieties of biotite granodiorite porphyry show bands of euhedral feldspar alternating with bands of biotite laths.

Sedimentary inclusions are represented by schistose and quartzitic fragments, perhaps derived from the Beartooth and Colorado formations which are generally quartzitic. Recrystallized, interlocking quartz grains from .2 to 1.0 mm. in diameter compose the bulk of the rock fragments (Fig. 8). Variable amounts of biotite scraps, kaolinized feldspars, chlorite, and limonite occur interstitially with the quartz. Some fragments which contain seggregations of biotite are distinctly schistose.

Matrix.—The gray to black matrix of the breccia consists of finely crystalline magnetite, quartz, and orthoclase (Fig. 8). Rarely secondary cuprite occurs as irregular grains with the magnetite. The matrix may comprise from 10 to 75 per cent of the breccia but an average specimen consists of about 65 per cent fragments and 35 per cent matrix. However, the matrix itself is a microscopic breccia at least half of which consists of fragments. Thus the average matrix content is actually around 15 to 20 per cent.

The magnetite forms extremely fine-grained aggregates. The individual grains frequently showing octahedral outlines range from .01 to .05 mm. The aggregates are distributed interstitially among the grains of orthoclase and quartz where the magnetite appears to be the principal cementing agent (Fig. 8). It is possible, however, that residual magmatic fluids originally deposited quartz and orthoclase between the freshly broken surfaces of the rock fragments. Later high temperature mineralization may have introduced the magnetite, which then partially replaced the primary felsic matrix. The replacing magnetite is interstitial to the quartz and orthoclase. Both the quartz and orthoclase are corroded marginally by magnetite, while occasional veins of magnetite cut the earlier quartz and orthoclase of the matrix.

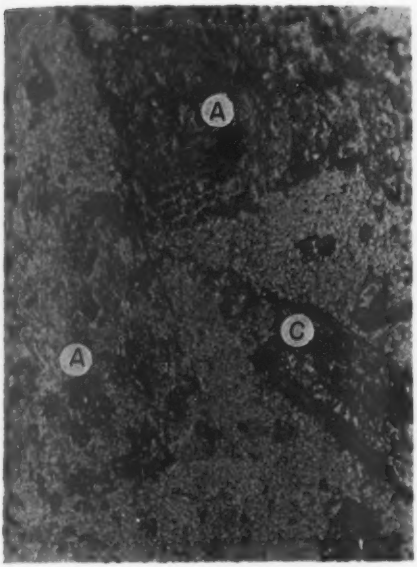

FIGURE 1

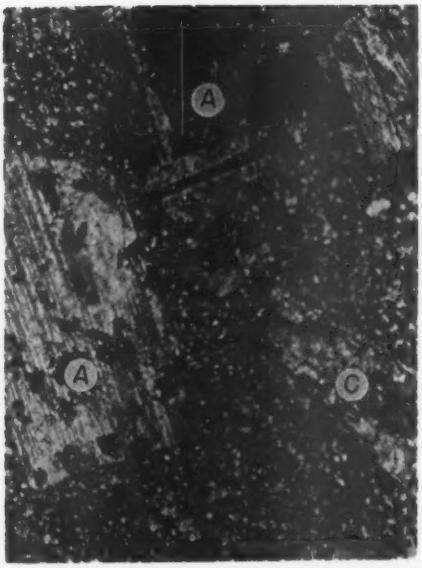

FIGURE 2

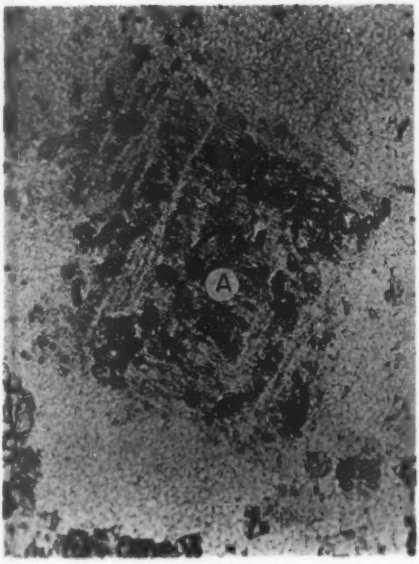

FIGURE 3

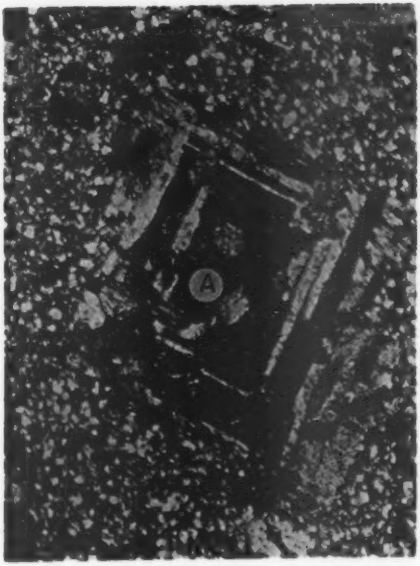

FIGURE 4

PHOTOMICROGRAPHS OF THIN SECTIONS OF UPPER AND LOWER SILLS

(1) Upper sill near Ivanhoe-Lovers Lane fault in railroad cut north of Whitewater Creek. Andesine (A) partly replaced by epidote and sericite. Hornblende replaced by chlorite (C). Plain light. X75. (2) Same as (1) Crossed nicols. X75. (3) Lower sill from southwest portion of area. Andesine (A) partly replaced by epidote. Plain light. X75. (4) Same as (3). Crossed nicols. X75.

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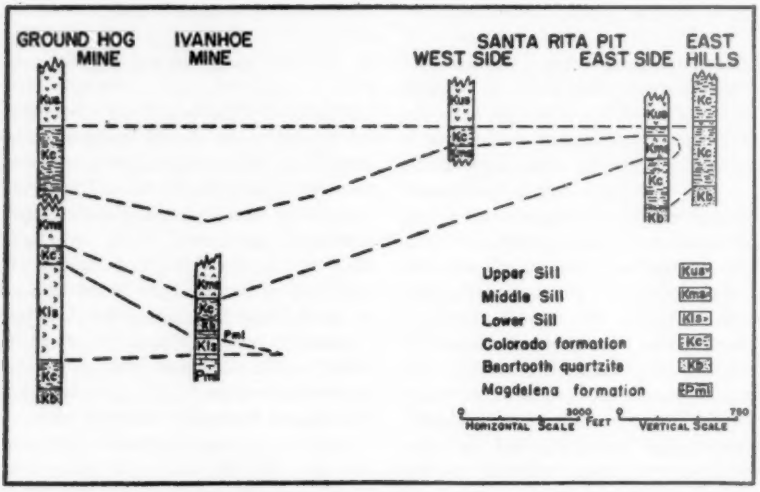

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Magnetite is usually present as a primary accessory mineral; apatite is less common. The ground mass consists of a mosaic of quartz grains about .01 mm. in diameter, and is usually clouded by such alteration minerals as chlorite, epidote, calcite, sericite, or limonite.

The Middle sill is dull green to buff. Phenocrysts (Pl. 3, figs. 1, 2) are smaller and more numerous than in the Upper sill, yielding an equigranular appearance. The component minerals are small and, in many cases, obscured by alteration. Small andesine laths make up about half of the rock, and prismatic crystals altered to epidote and chlorite are common. Quartz and biotite phenocrysts are lacking while magnetite is sparse and erratic in distribution. The groundmass consists of fine-grained quartz and scattered alteration min-

erals. The sill can be distinguished from the adjacent sills by (1) finer-grained, more equigranular texture, (2) absence of quartz phenocrysts, (3) absence of biotite phenocrysts. The Middle sill is further characterized in thin section by a general lack of magnetite and characterized in thin section by a general lack of magnetite and apatite.

Both the Middle and Upper sills are in places sheeted parallel to the contact with enclosing rocks as shown in exposures of the Upper sill in the valley across Whitewater Creek from the Kennecott precipitating plant and near the base of the Middle sill southwest of the Lucky Boy intrusive.

Hanover Intrusive

The Hanover and Santa Rita intrusives are granodiorite porphyry, being similar both petrographically and in general relations, although the alteration and mineralization differ markedly.

The granodiorite porphyry forming the Hanover stock is a likely equivalent of the Santa Rita granodiorite porphyry. The proximity of the two known masses, the similarity of regional structure, the occurrence in both of aplites, the magnetite zones bordering both intrusives, the similarity of texture and mineral content, all point to contemporaneous invasion from the same magma. A deep-seated connection between the two igneous masses may exist and the intrusives of Hanover and Santa Rita are likely cupolas of a common deep-seated batholith.

The granodiorite porphyry of the Hanover stock forms a body of relatively unaltered rock in a region of intense mineralization. The lack of hydrothermal alteration in the Hanover intrusive is emphasized by the apparent absence of pyrite and only the slightest development of sericite, chlorite, and argillic (Lovering, 1941) alteration.

Even the grandiorite porphyry of the least altered stage found in the North Pit at Santa Rita has undergone more alteration than may be observed in the porphyry at Hanover. Thus the Hanover intrusive by inference indicates the original character of the Santa Rita rock prior to alteration.

The Hanover granodiorite porphyry is generally coarsely crystalline, showing prominent phenocrysts of plagioclase, hornblende, and biotite, ranging from porphyritic to granular (Pl. 3, fig. 4). The ground mass which makes up 40–70 per cent of the rock is dense and

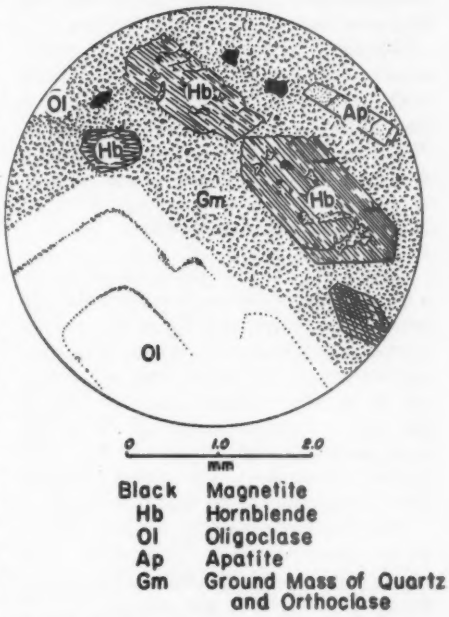


FIGURE 7.—HANOVER GRANODIORITE PORPHYRY

gray to buff. In places it increases in amount and decreases in grain size to enhance the porphyritic appearance (Fig. 7). Lustrous oligoclase phenocrysts measure 0.5–10 mm. long and show zoning as well as albite and pericline twinning. The dull-white and gray alteration of the feldspar phenocrysts at Santa Rita is missing. Hornblende (Fig. 7) appears prominently in slender dark-green pleochroic crystals measuring as much as 7.0 mm. long. Biotite phenocrysts occur as barrel-shaped crystals up to 5.0 mm. across. Some chlorite development occurs along cleavage traces.

The estimated abundance of the rock-forming minerals is: feldspar, 70 per cent; hornblende, 10–20 per cent; quartz, 10–15 per cent; biotite, 5 per cent. Accessory minerals include diamond-shaped euhedral sphene, apatite, and zircon. Magnetite, common as irregular masses and grains of 0.1 to 0.6 mm. diameter, is usually

found within or near hornblende prisms or along the edges of sphene crystals. Sulfide mineralization is noticeably absent. In porphyritic granodiorite, phenocrysts of plagioclase, hornblende, and biotite occur in a granular ground mass of quartz and orthoclase.

Oligoclase and hornblende were the earliest silicate minerals to crystallize in the Hanover stock. Quartz and orthoclase were later (Pl. 3, fig. 4). Biotite may belong in this second group. Magnetite appears to be the latest of the common mineral constituents.

Santa Rita Intrusive

Description.—The Santa Rita intrusive forms a rounded body about a mile across and is best exposed in the copper pits. The stock is apically truncated and is bounded by metamorphosed sedimentary rocks that have been partially removed by recent mining operations. (Fig. 2; Pl. 1). The alteration study of the Santa Rita stock presumes a single intrusive mass of biotite granodiorite porphyry. The original characteristics are suggested by the least altered portion.

The granodiorite porphyry has been referred to as quartz porphyry (Brinsmade, 1908), quartz diorite porphyry (Sully, 1909), diorite porphyry (Ball, 1910), and quartz monzonite porphyry (Lindgren, Gaton and Gordon, 1910); Paige, 1912, 1916; Rickard, 1923). More recently the rock has been described as granodiorite (Landon, 1929) and granodiorite porphyry (Spencer and Paige, 1935) although S. F. Emmons (1899) regarded the igneous rock of Santa Rita as being "probably granodiorite."

Landon (1929) has estimated the mode of the intrusive rock as orthoclase, 12%; quartz, 15%; oligoclase, 63%; hornblende, 8%; and acessories 2%. The high percentage of hornblende and the absence of biotite are more characteristic of the near-by Hanover stock and do not correspond to the many sections studied in this investigation.

Spencer and Paige (1935, p. 36), describing the porphyry from the exposures in the North Pit, observe: "A careful estimate indicates that the proportions of andesine and orthoclase are respectively about 40 to 16 per cent, so that the stock falls under the classification of granodiorite rather than quartz monzonite."

The Santa Rita granodiorite porphyry contains evenly distributed phenocrysts in a dense gray groundmass although, like the Hanover intrusive, this porphyry also shows some variations in texture. Lustrous, striated green-gray feldspar phenocrysts are common, while coarse hornblende and quartz occasionally occur.

The plagioclase phenocrysts lie between calcic oligoclase and sodic andesine. Zoning and albite twinning are apparent in all phenocrysts and some show both albite and pericline twinning. The crystals have been corroded and embayed by the groundmass quartz and orthoclase of late crystallization.

The biotite flakes are generally about 2 mm. across. Hornblende phenocrysts with pale- to olive-green pleochroism occur infrequently. Although ordinarily the most characteristic mineral, occasionally the porphyry shows little biotite.

The groundmass consists of equigranular, interlocking grains of quartz and slightly sericitized orthoclase. The quartz and orthoclase were probably contemporaneous although some quartz is later. Generally the feldspar in the groundmass is fresher than the phenocryst feldspar. Interstitial magnetite, pyrite, and limonite occur throughout the groundmass. Accessory sphene, apatite, zircon, and rutile are found. Magnetite is a common constituent and occurs as irregular or skeletal grains 0.3–1.0 mm. in diameter.

The Santa Rita prophyry is distinguished most sharply from the Hanover prophyry by the dominance of biotite in the former and hornblende in the latter.

Sequence of Crystallization.—The texture of the Santa Rita biotite granodiorite porphyry points toward: 1. An earlier stage of crystallization of the euhedral phenocrysts. 2. A later stage characterized by the solidification of residual liquors to form the interstitial mass of orthoclase, quartz, and biotite.

Phenocrysts of hornblende were among the earliest to crystallize. Abundant iron-rich biotite followed and in places forms reaction rims about the earlier amphibole. Contemporaneous with the crystallization of the hornblende and biotite, plagioclase feldspar crystallized as zoned crystals with cores of andesite becoming increasingly sodic outwards to the oligoclase margins. Quartz phenocrysts were probably the latest to form.

As the early phenocrysts were transported in the solid phase through the residual liquors of the congealing stock, some suffered corrosion and resorption. Quartz was exceptionally vulnerable being everywhere attacked by residual solutions believed to have been highly alkaline. Hornblende phenocrysts likewise were shredded and embayed. Biotite and plagioclase, prior to the complete solidification of the granodiorite, retained and extended their boundaries at the expense of the ground mass liquors to form the largest crystals among the early minerals.

The minor accessories sphene, apatite, zircon, and rutile were generally early, crystallizing with the phenocrysts. Magnetite followed, with the crystallization of the ground mass and still later in the post-magmatic stage of deuteric and high-temperature mineralization. Some apatite embedded in quartz may likewise be post-magmatic.

Periods of mineralization.—Mineralizing solutions were guided in their movement upward through the granodiorite porphyry and the intruded formations by porosity due to hydrothermal action and intense fracturing. The first wave of metallic deposition formed magnetite in irregular grains or small crystals. The Whim Hill breccia was cemented by magnetite and orthoclase. Massive magnetite veins also cut through the contact phases bordering the stock. Although magnetite was originally distributed throughout the stock as disseminated, interstitial grains in the granodiorite porphyry, most of the iron-rich solutions rose later through the border phases of the intrusive. Magnetite, pyrite and in a few places chalcopyrite were formed by replacement in the calcareous rocks of the nearby Syrena Formation.

The magnetite-precipitating solutions subsided as a period of aplitic injection followed. The residual felsic solutions filled prominent parallel fissures in the granodiorite porphyry.

The next surge of mineralizers introduced pyrite and small amounts of molybdenite. Pyrite is ubiquitous in the granodiorite porphyry and replaces earlier magnetite. Pyrite marginal to magnetite grains is rarely found in the fresh granodiorite porphyry. However, pyrite and magnetite appear mutally exclusive in the altered rock. The later pyrite frequently cuts through the veins and beds replaced by magnetite in the Syrena formation.

The quartz porphyry dikes of the Santa Rita and Hanover districts were injected at about this stage and appear to separate the primary mineralization at Santa Rita into an early and late epoch. The quartz-bearing granodiorite dikes cut the pre-mineral hornblende granodiorite porphyry dikes which lie west and northwest in the Hanover-Ground Hog zone. In the Santa Rita intrusive, a prominent quartz porphyry dike has been emplaced along north to northeasterly fissures. Other quartz porphyry dikes found in outcrops of the Central Island have similar alignment.

Quartz veins were formed throughout an extended period of mineralization. Having started to form prior to the injection of the quartz porphyry dikes, the pyrite continued until the close of primary mineralization.

Veins and disseminated grains of chalcocite occur most abundantly in the altered porphyry, and the mineral is later than pyrite at Santa Rita. It is believed that the chalcocite may belong to a late phase of hypogene mineralization as well as being a participant in supergene enrichment.

Whim Hill Breccia

Description.—A cemented fragmental rock known locally as the Whim Hill breccia (Landon, 1929) forms two areas of exposure in the northern part of the Santa Rita stock (Pl. 1). The larger comprises an area of over 40,000 square feet and forms a somewhat elongate mass in the central part of the North Pit where it encloses a rounded block of biotite granodiorite porphyry. The second body which is much smaller is found on the northern edge of the Central Island between the North and South Pits. The breccia masses are bounded by slightly to moderately altered biotite granodiorite porphyry and occupy the core of the Santa Rita stock.

The breccia forms a mass of angular blocks cemented by a matrix rich in magnetite (Fig. 8; Pl. 5, fig. 1). The fragments represent a number of rock types known to occur in the stratigraphic section (although definite sill rock was not identified). Broken pieces of biotite granodiorite porphyry predominate. Angular and rounded fragments of indurated shales and quartzites which probably came from the Beartooth and

Colorado formations may be seen. The fragments of biotite granodiorite porphyry are somewhat altered but not highly, hence the breccia may be considered as having been

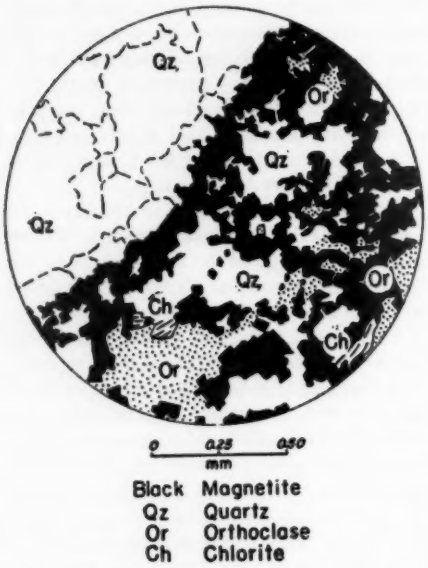


FIGURE 8.—WHIM HILL BRECCIA. Boundary between quartz fragment and magnetite matrix.

formed subsequent to some of the earliest hydrothermal alteration of the surrounding granodiorite porphyry.

On the whole, the breccia is compact and firmly cemented, but small miarolitic cavities appear occasionally within the matrix. One cavity about an inch across was lined with euhedral crystals of magnetite. Veins of aplite have been found cutting the breccia.

Fragments.—Generally fragments of the breccia range from microscopic dimensions to angular blocks 9–12 inches on a side, but occasional well-rounded or even spherical fragments indicate considerable milling after brecciation. Close observations of the matrix show angular fragments .5–2.0 mm. in diameter.

The biotite granodiorite fragments vary from nearly equigranular to coarsely porphyritic. Phenocrysts of oligoclase, hornblende, biotite, and less commonly quartz occur in variable ground masses of orthoclase, rare oligoclase, quartz, biotite, and chlorite. Accessories include magnetite, apatite, rutile, and zircon. The phenocrysts of oligoclase may be fresh or altered to such a degree that the prominent plagioclase twinning is obscured. The hornblende, found only as unreplaced cores and amphibole outlines, is replaced by chlorite and laths of biotite. The phenocrysts of original biotite are but slightly altered to chlorite. In thin sections some varieties of biotite granodiorite porphyry show bands of euhedral feldspar alternating with bands of biotite laths.

Sedimentary inclusions are represented by schistose and quartzitic fragments, perhaps derived from the Beartooth and Colorado formations which are generally quartzitic. Recrystallized, interlocking quartz grains from .2 to 1.0 mm. in diameter compose the bulk of the rock fragments (Fig. 8). Variable amounts of biotite scraps, kaolinized feldspars, chlorite, and limonite occur interstitially with the quartz. Some fragments which contain seggregations of biotite are distinctly schistose.

Matrix.—The gray to black matrix of the breccia consists of finely crystalline magnetite, quartz, and orthoclase (Fig. 8). Rarely secondary cuprite occurs as irregular grains with the magnetite. The matrix may comprise from 10 to 75 per cent of the breccia but an average specimen consists of about 65 per cent fragments and 35 per cent matrix. However, the matrix itself is a microscopic breccia at least half of which consists of fragments. Thus the average matrix content is actually around 15 to 20 per cent.

The magnetite forms extremely fine-grained aggregates. The individual grains frequently showing octahedral outlines range from .01 to .05 mm. The aggregates are distributed interstitially among the grains of orthoclase and quartz where the magnetite appears to be the principal cementing agent (Fig. 8). It is possible, however, that residual magmatic fluids originally deposited quartz and orthoclase between the freshly broken surfaces of the rock fragments. Later high temperature mineralization may have introduced the magnetite, which then partially replaced the primary felsic matrix. The replacing magnetite is interstitial to the quartz and orthoclase. Both the quartz and orthoclase are corroded marginally by magnetite, while occasional veins of magnetite cut the earlier quartz and orthoclase of the matrix.

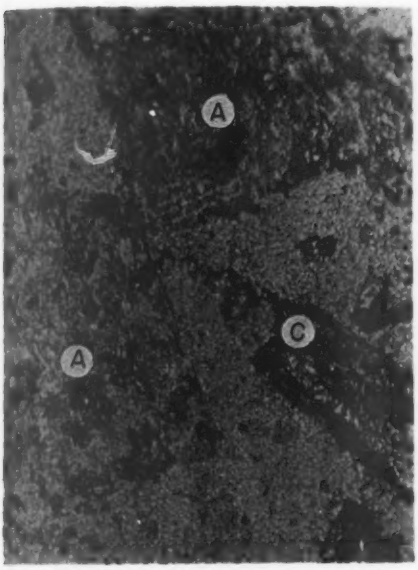
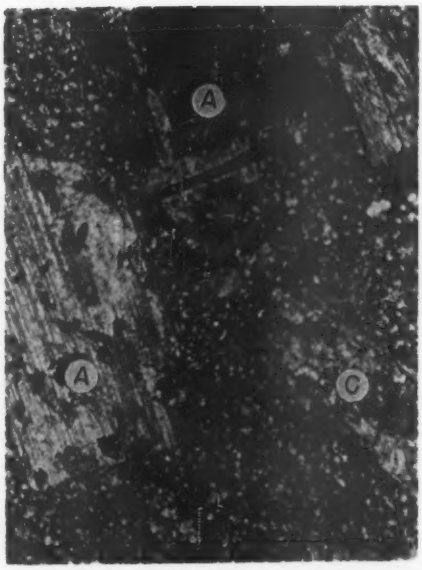


FIGURE 1



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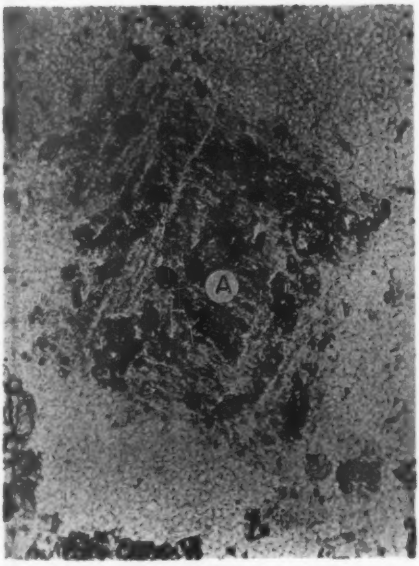

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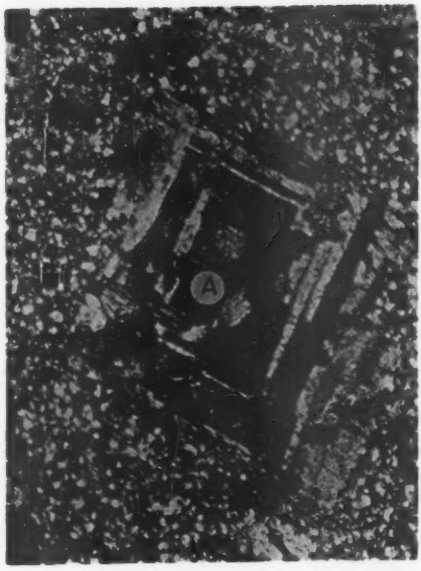
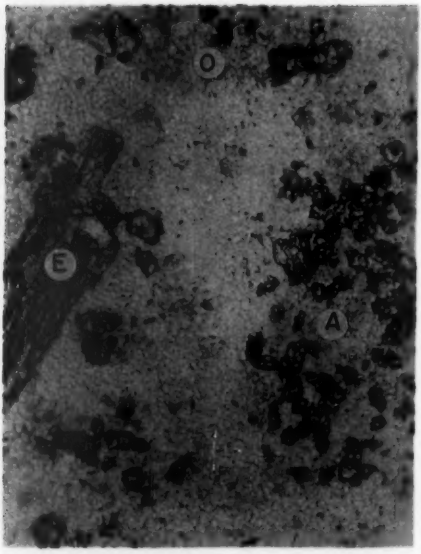


FIGURE 4

PHOTOMICROGRAPHS OF THIN SECTIONS OF UPPER AND LOWER SILLS

(1) Upper sill near Ivanhoe-Lovers Lane fault in railroad cut north of Whitewater Creek. Andesine (A) partly replaced by epidote and sericite. Hornblende replaced by chlorite (C). Plain light. X75. (2) Same as (1) Crossed nicols. X75. (3) Lower sill from southwest portion of area. Andesine (A) partly replaced by epidote. Plain light. X75. (4) Same as (3). Crossed nicols. X75.



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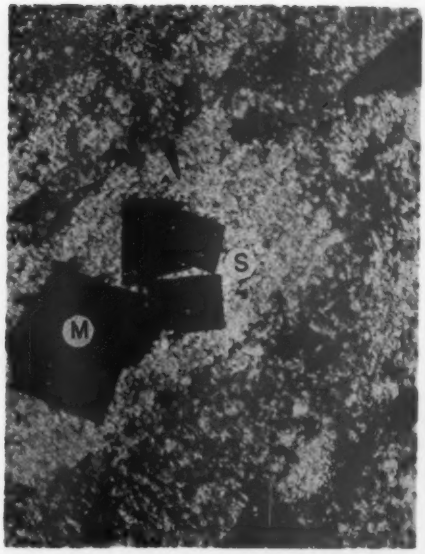

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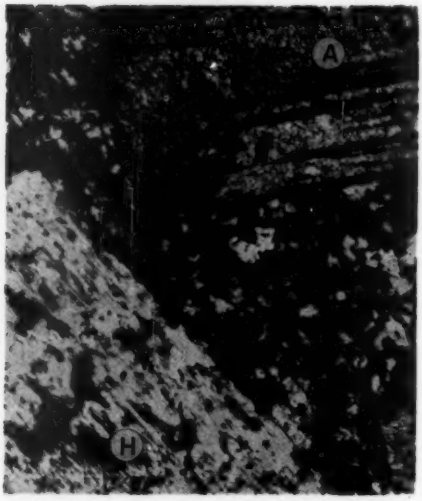

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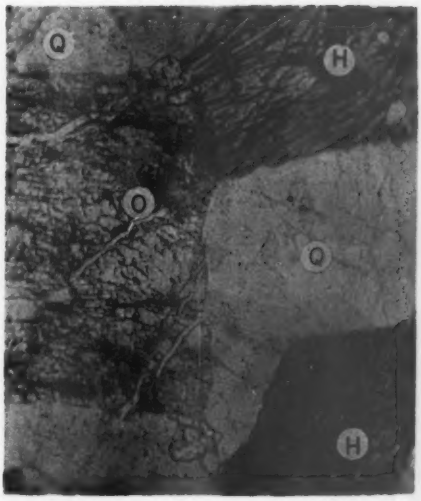
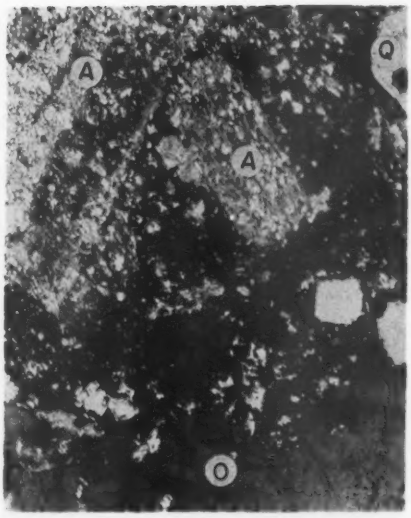


FIGURE 4

PHOTOMICROGRAPHS OF SILL AND PORPHYRY THIN SECTIONS

(1) Middle sill. Andesine (A) partly replaced and hornblende completely replaced by epidote (E). Some orthoclase (O) remains. X75. (2) Sericitic alteration in the same sill. Relict feldspar crystal now sericite (S) surrounds original magnetite (M). Crossed nicols. X75. (3) Hornblende porphyry from Empire zinc mine with andesine (A) and hornblende (H). Crossed nicols. X75. (4) Hanover granodiorite porphyry with quartz (Q), hornblende (H) and orthoclase (O). X75.

FIGURE 1



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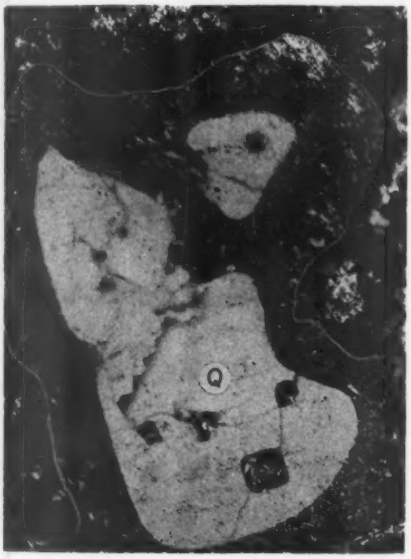


FIGURE 3

FIGURE 4

PHOTOMICROGRAPHS OF QUARTZ PORPHYRY AND LATITE

(1) Quartz porphyry, Empire zinc mine. Plain light. X75. (2) Quartz porphyry, Empire zinc mine. Andesine (A) partly altered to sericite. Orthoclase (O) is fresh. Crossed nicols. X75. (3) Quartz porphyry, Empire zinc mine, showing quartz (Q) phenocryst rimmed with secondary quartz. Edge of grain outlined in white. Crossed nicols. X75. (4) Latite from 4th level, Empire zinc mine. Oligoclase-andesine (A) and biotite (B) in groundmass of feldspar laths. Plain light. X75. Quartz (Q), andesine (A), orthoclase (O), chlorite after biotite (C).

FIGURE 1. WHIM HILL BRECCIA EXPOSURE, NORTH PIT
Typical exposure of Whim Hill breccia in bank at bottom of northwest wall of North Pit, Santa Rita. Angular light-colored fragments, chiefly biotite granodiorite, included in dark matrix highly impregnated with magnetite.

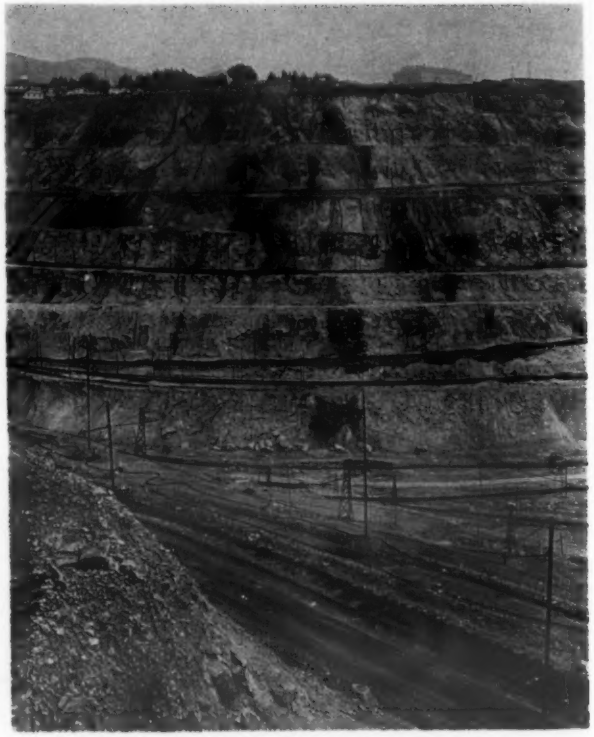


FIGURE 2. QUARTZ PORPHYRY DIKES ON NORTH WALL, SOUTH PIT
Quartz porphyry dikes shown as dark exposures passing upward from right to left. Recent operations on the 5942 (lowest) bench had removed much of the oxidized material, hence apparent interruption in branching dike zone.

WHIM HILL BRECCIA AND PORPHYRY DIKES IN SANTA RITA OPEN PITS

FIGURE 1. MINOR FAULT ON THE SOUTHWEST WALL, SOUTH PIT
Southeastward-dipping fault brings middle quartz diorite sill (hanging wall) into contact with altered granodiorite porphyry of Stage 3 (foot wall). Sill follows rim of pit on both sides of fault. Ground water has percolated along this structure as shown by dark stained area in hanging wall. Leached, iron-stained zone noticeably follows fault.

FIGURE 2. QUARTZ PORPHYRY DIKES ON SOUTH WALL, SOUTH PIT
Two prominent iron-stained quartz porphyry dikes may be followed up the south wall. Less prominent branching dike runs between them on the upper benches.

DIKE AND FAULT EXPOSURES, SOUTH PIT, SANTA RITA

FIGURE 1. CARBONATE FAULT ZONE, LEE HILL FLUX QUARRY
Southeastward-dipping fault zone shown forming the wall of a flux quarry west of South Pit. Hanging wall is upper quartz diorite sill, and footwall is Colorado quartzite. Fault zone consists of a crushed limonite cemented breccia polished by slickensides.

FIGURE 2. FAULT ON WEST WALL, SOUTH PIT
Middle quartz diorite sill (dark rock) lies in contact with Colorado and Beartooth quartzite (light-colored rock) along southward-dipping fault zone of gouge. Latite porphyry dike within quartzite appears to the right of fault.

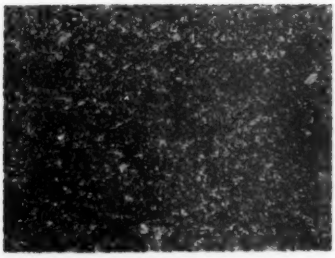
FAULTS EXPOSED IN WORKINGS AT SANTA RITA

FIGURE 1. STAGE 4, SILICIFIED GRANODIORITE PORPHYRY WITH INTERSECTING QUARTZ VEINS

Recently blasted blocks of Stage 4 silicified granodiorite porphyry on the 5942 bench of the south wall, South Pit, Santa Rita. Typical specimens containing intersecting quartz veins.

FIGURE 2. SILICIFIED GRANODIORITE PORPHYRY (WHITE) PENETRATING THE SYRENA (DARK GRAY)

Projection of intrusive rock Stage 4 penetrates overlying block of highly metamorphosed Syrena sedimentary rocks at base of north wall of South Pit, Santa Rita. Light-colored rock in foreground is silicified granodiorite porphyry. Dark formations comprising lower benches are part of Syrena formation. Rock mapped as biotite granodiorite porphyry of Stage 2, but apparently a hybrid formed by intermingling of granodiorite porphyry with Syrena, occurs along upper benches.



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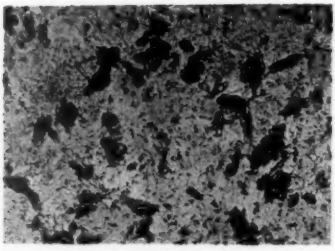

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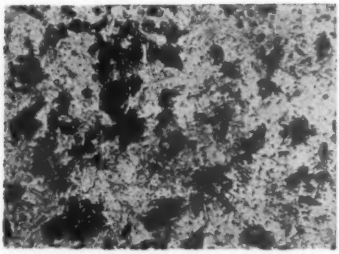

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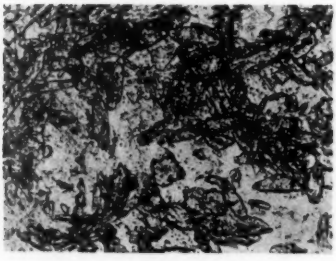


FIGURE 4

FIGURE 5

MICROGRAPHS SHOWING EPIDOTIZATION

Five stages in the transition from shale (1) to massive epidote (5) as shown in thin section.

Origin.—The association with igneous rocks in the core of an eruptive mass; the rounded outlines of compact intrusive units; the high temperature character of the magnetite mineralization of the matrix; and the lack of gouge, associated fracture patterns or linear relationships all point toward igneous origin of the breccia. It seems to be a pipe of roughly elliptical outline extending vertically to considerable depth, although it could consist of irregular masses which either coalesce or diverge downward.

Three hypotheses seem worthy of consideration:

1. The breccia consists of fragmented blocks formed in late Tertiary volcanic necks or pipes.
2. It is a friction breccia border formed at time of intrusion of the stock into the sedimentary formations.
3. It is an internal breccia formed at a late stage of consolidation.

(1) Extensive volcanism took place in the district during the middle or late Tertiary as shown by hundreds of feet of successive flows of latite with underlying tuffs which form the hills south and east of the Santa Rita. Spencer and Paige (1935, p. 40) believe that these lavas once completely covered the Santa Rita area. If so, this body of breccia could represent an uncovered volcanic throat filled with angular fragments of wall rock broken with explosive violence.

However, fragments are not cemented by material common to the volcanic series, and are not sufficiently heterogeneous to indicate a pipe-like body of great depth. Most of the rock fragments are granodiorite porphyry with minor amounts of quartzites and altered argillaceous sedimentary rocks that seem to have come from the intruded Cretaceous formations. Blocks of the extensive Paleozoic limestones are missing. Neither have fragments of latite been carried down. Finally, the breccia seems to belong in the period of solidification of the Santa Rita stock since it is cut by aplite and quartz veins representing the residual solutions of the crystallizing magma. The presence of both igneous and sedimentary fragments of near-by formations supports the view that the breccia is syngenetic with the intrusive which contains it, and represents a crushed border phase. Both sedimentary and igneous blocks would have subsided into the crystallizing magma as the stress of upward movement and friction with the wall rocks continued.

However, the breccia occupies the core of the stock. Hence, it could hardly represent a crushed zone between the wall rock and the intrusive. A marginal breccia does exist along the edge of an intrusive about 2 miles west, but this breccia is associated with the later Lucky Boy intrusive.

It seems unlikely that the Whim Hill breccia formed in the early stages of emplacement and solidification. Nor did it likely result either from friction between the wall rock and the intrusive or between portions of the intrusive in differing stages of crystallization. It is reasonable to believe that the breccia formed after the igneous body reached its final resting place and crystallization had been largely completed.

(3) The fragments of granodiorite porphyry are broken pieces of rock already crystallized, shattered by internal activity within the stock. The migration of residual liquors may have left unsupported walls of solidified prophyry to slump into the fluid magma, and the solidified granodiorite porphyry may have been undermined by late corrosive, mineralizing fluids. Possibly liquids or gases or both forced their way upward under great pressure within the core of the intrusive and burst forth with explosive violence to escape through shattered walls of porphyry. The intensity of this shattering can be traced to fragments of microscopic size. These fragments were then cemented by the remaining felsic and iron-bearing solutions which were largely liquid with some associated gases. The occasional cavities and highly abraded inclusions suggest that gases were involved in the formation and later cementation of the breccia. That the Whim Hill breccia was formed entirely by forces within the stock at a late stage of igneous activity seems likely. Later aplitic and siliceous solutions filled cracks in the cemented breccia.

Lucky Boy Intrusive

The Lucky Boy intrusive is a term applied to the mass of igneous rock and igneous breccia exposed on the Lucky Boy and near-by claims in the hills south of Wimsattville. It is difficult to relate this intrusive to other igneous bodies

of the area because the intense rock alteration renders identification impossible. Hence the descriptive name "intrusive" is used. The intrusive includes part of the mineralized breccia mapped by Spencer and Paige (1935) and part of the adjacent latite. The rock is highly fractured and streaked with limonite. During the present work the boundary of the mass was only partly traced. Where studied the Lucky Boy intrusive was found to be bordered by the Colorado formation, the Syrena formation, and the Middle sill. Dike-like projections of the intrusive extend into the surrounding country rock.

The intrusive consists partly of light-gray porphyritic rock with doubly terminated quartz crystals and twinned euhedral orthoclase crystals in a buff to gray matrix. Perfect crystals of quartz and feldspar can be gathered from a road cut near Trevarrow's Garage at Wimsattville. Columns of biotite occur in some specimens. Thin section study adds little information to that which can be obtained megascopically. Rounded quartz phenocrysts are common. Feldspar is altered to calcite and sericite so that no twin angles can be measured. Biotite is replaced by muscovite and sericite. The groundmass consists of tiny quartz grains, sericite, calcite, and secondary quartz.

Most of the Lucky Boy intrusive is characterized by a breccia containing angular inclusions of fine-grained quartzite and shale in an igneous matrix. The fragments were probably derived from the Colorado formation. These inclusions are abundant along the edge of the igneous mass where it cuts the Colorado; hence the contact is usually marked by a breccia zone. Within the intrusive the distribution of fragments is quite irregular. Igneous rock which is free from inclusions may be seen in the road cut near Trevarrow's Garage and in a gully on the south end of the Syrena claim. At both places the country rock is the Syrena formation. At the edge of the intrusive along the road south of Wimsattville the Colorado is fractured and brecciated but not cemented. Here the overlying Colorado which was not actually invaded by the magma may have been fractured by the upward force of emplacement.

The relations between the Lucky Boy intrusive and other igneous rocks of the area are in doubt. The intrusive most nearly resembles quartz porphyry; there is a similarity both in mineral content and type of alteration. The alteration is far more intense than any observed in the Tertiary igneous rocks. At its southern edge the intrusive cuts a hornblende porphyry dike, the only known indication of age relationship. The Lucky Boy intrusive, therefore, is younger than hornblende porphyry, and the intensity of alteration suggests that the intrusive is older than the Tertiary igneous rocks. The similar petrology and age relations suggest a correlation with quartz porphyry. The relationship between the intrusive mass and the block of Tertiary gravels to the north cannot be determined because exposures are lacking.

Dikes

General description.—Aside from the aplite dikes found along portions of the margins of the two intrusives, two groups of granodiorite porphyry dikes and a later series of Tertiary latite dikes have been recognized. The granodiorite dikes are closely related to the granodiorite porphyry stocks and like the stocks are regarded as Laramide in age. The latite dikes are among the youngest igneous rocks of the region.

The granodiorite porphyry dikes are well known from workings at the Empire Zinc, Zinc, Oswaldo, and Ground Hog mines, where they are associated with zinc ore bodies. At each mine two types are recognized:

1. Pre-ore dikes which are characterized by plagioclase and hornblende.

2. Later dikes which are pre-ore at the Ground Hog mine and late- or post-ore in the Hanover area. These dikes are more porphyritic than the earlier dikes and characterized by phenocrysts of plagioclase, biotite, quartz, and large poikilitic orthoclase crystals.

Investigation of the dikes at the three localities aided by study of over 100 thin sections indicates that the dikes are similar and can be correlated from place to place. The dikes are designated locally by various names. For example, epidotized pre-ore dikes at the Empire Zinc mine ("Ek") correspond to those designated as "black birdseye" porphyry at the Ground Hog mine and "A type" at the Oswaldo mine. The present report distinguishes the two dike types by the most distinctive mineral, other than the ever-present feldspar. Thus the

dikes are designated hornblende granodiorite porphyry and quartz granodiorite porphyry, or more simply, hornblende prophyry and quartz porphyry.

The following table relates these names to local terminology.

Dike type	Empire zinc mine	Oswaldo mine	Ground hog mine
Quartz granodiorite porphyry	Kbi; some Tla, Tlaq	B type	White birdseye porphyry
Hornblende granodiorite porphyry	Ek; most dikes with Greek names (Gamma dike, Eta dike, etc.)	A type	Black birdseye porphyry

Aplite.—The aplites of the North Pit occur as stringer zones in granodiorite porphyry which constitute three linear, finger-like bodies lying more or less parallel to the major axis of the Santa Rita stock. The general trend of the bodies is N30°W to N45°W. Two small aplite-bearing areas 35–80 feet wide may be traced longitudinally for 400 feet from the second bench above the reservoir to the upper benches in the North Pit. On the upper benches, the aplites are poorly exposed and are difficult to distinguish from the biotite granodiorite porphyry. The third and longest of the aplite zones seems to branch from the easternmost of the two smaller ones. What is probably a continuation of this zone is found on the south shore where it widens from 8 to 250 feet at the southeast rim of the North Pit.

The aplites in the North Pit frequently show an unusual horizontal attitude. Thin lenses and sheets of fine-grained, equigranular, pale-pink to buff aplite are interspersed with coarse-grained, relatively fresh biotite granodiorite porphyry. The aplite sheets measure up to 5 or 6 inches wide. Vertical feeder dikes exist but are not as well exposed. Occasionally veins of aplite not more than 2 inches wide cut both the fresh biotite granodiorite porphyry and the Whim Hill breccia. Aplite was observed at one place in the more highly altered rock of the South Pit.

Microscopic study of the aplites reveals a typically fine-grained, equigranular texture consisting chiefly of quartz and orthoclase with subordinate biotite and interstitial magnetite. The grains of the anhedral quartz and orthoclase are small in a single section or band and vary from .1–.8 mm. thick. Frequently the aplites show a textural banding. Fine equigranular bands of quartz and orthoclase .04–.3 mm. thick may alternate with coarser bands ranging in grain size from .2–1.0 mm. This banded microscopic texture indicates the dike-like injected nature of the rock. Biotite flakes occur occasionally measuring .08–.2 mm. thick.

Although the normal aplite is non-porphyritic, mixed phases of biotite granodiorite porphyry and aplite occur which contain phenocrysts. Phenocrysts in the adjoining porphyry appear to favor the marginal zones within the aplite. An extremely thin band of aplite will often alternate with a thin band of porphyry thus reproducing microscopically the field relationships. The intermingling of aplite and granodiorite is emphasized not only by the bands of aplite of varying grain size, which alternate with porphyry, but by additional bands of vein quartz and orthoclase intergrown with quartz which occur with the biotite laths oriented in the direction of banding.

Prominent micrographic and vermicular intergrowths of quartz and orthoclase occur along the contact between the aplite and the biotite granodiorite porphyry (Fig. 9). They may represent simultaneous crystallization or replacement of the feldspar phenocrysts by quartz. Such intergrowths are not found elsewhere in the biotite granodiorite porphyry and appear to have been induced by the injection of the aplites.

The aplites have been subjected to alteration comparable to that observed in the associated biotite granodiorite porphyry. In some aplites, feldspars are partially sericitized. In others, the feldspars have been replaced completely by sericite and kaolinite. Occasional biotite crystals may be indicated by interstitial patches of chlorite. Highly altered aplites show recrystal-

lized quartz and vein quartz replacing the sericitized orthoclase. Veins of late quartz are found to intersect both the aplite and the porphyry. Limonite occurs as a secondary prod-

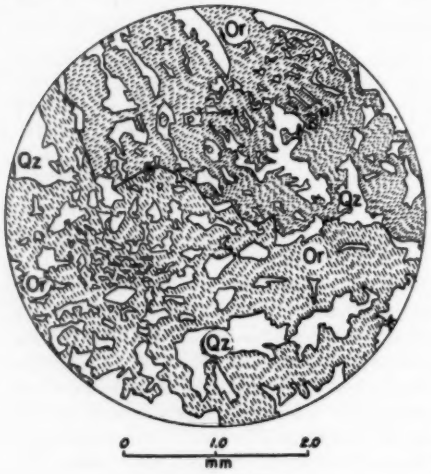


FIGURE 9.—MICROGRAPHIC INTERGROWTH OF QUARTZ AND ORTHOCLASE ALONG CONTACT BETWEEN APLITE AND BIOTITE GRANODIORITE PORPHYRY, NORTH PIT

uct after magnetite and biotite. Metallic sulphides appear to be absent.

Linear arrangement of the aplite zones in the North Pit may indicate structural control. The zones are parallel to one another and also lie parallel to the trend of the least altered zone in the Santa Rita stock. It seems that the aplitic material was injected into the granodiorite porphyry along lines of weakness corresponding in direction to the inclination of the contact with the invaded sedimentary formations. The bedded nature of the aplites would indicate their emplacement along a somewhat sheeted zone. Intersecting vertical fissures may have yielded the orientation preserved in the strike of the aplite zones.

The aplites presumably were injected into the porphyry after the formation of the Whim Hill breccia, representing the final surge of the residual felsic liquor of the crystallizing Santa Rita granodiorite intrusive. They show no signs of mineralization other than the hydrothermal alteration common to the Santa Rita stock. Early quartz veins are found cutting through the bedded aplite-porphyry zone. Had alteration been more intensive in this eastern portion of the North Pit, the aplites and their associated biotite granodiorite porphyry would have been changed to silicified rock and this interesting relationship might have been completely obscured. It seems likely that similar aplitic zones were formed in the granodiorite porphyry of the South Pit, but their presence has been obscured by subsequent hydrothermal alteration. Only one exposure of aplite was observed.

Aplite dikes of a similar character border the southern rim of the Hanover intrusive. Float containing aplite may be found within the intrusive area. These aplites appear to form a single marginal zone rather than parallel zones as at Santa Rita. Where the zone has been cut in the Nason tunnel of the Empire Zinc Company at Hanover, a group of horizontal parallel dikes has been exposed. This occurrence is quite similar to that found in the North Pit. The alteration, however, is much less evident at Hanover.

Hornblende granodiorite porphyry.—Hornblende granodiorite porphyry dikes crop out extensively in the area between Hanover and the Ground Hog mine where they cut the sills and sedimentary rocks. Most dikes were emplaced along pre-existing fractures and conform to the regional fault pattern. At Hanover both faults and dikes have northerly strikes. In the Ground Hog mine (Fig. 10), the trend is more nearly northeast. Some dikes are solid units, but frequent wide anastomosing bodies include masses of country rock. Near the Ivanhoe shaft is a mixed dike and country rock complex several hundred feet wide. This feature has been explained as the result of intrusion along a complex series of linked fractures (Lasky, 1936d, p. 36).

In hornblende prophyry dikes, important bodies of the commercial zinc ore have been found as replacements of adjacent limestone beds. The dike rock shows considerable variation in appearance from place to place but thin sections reveal that the mineral assemblage is essentially constant; differences in appearance

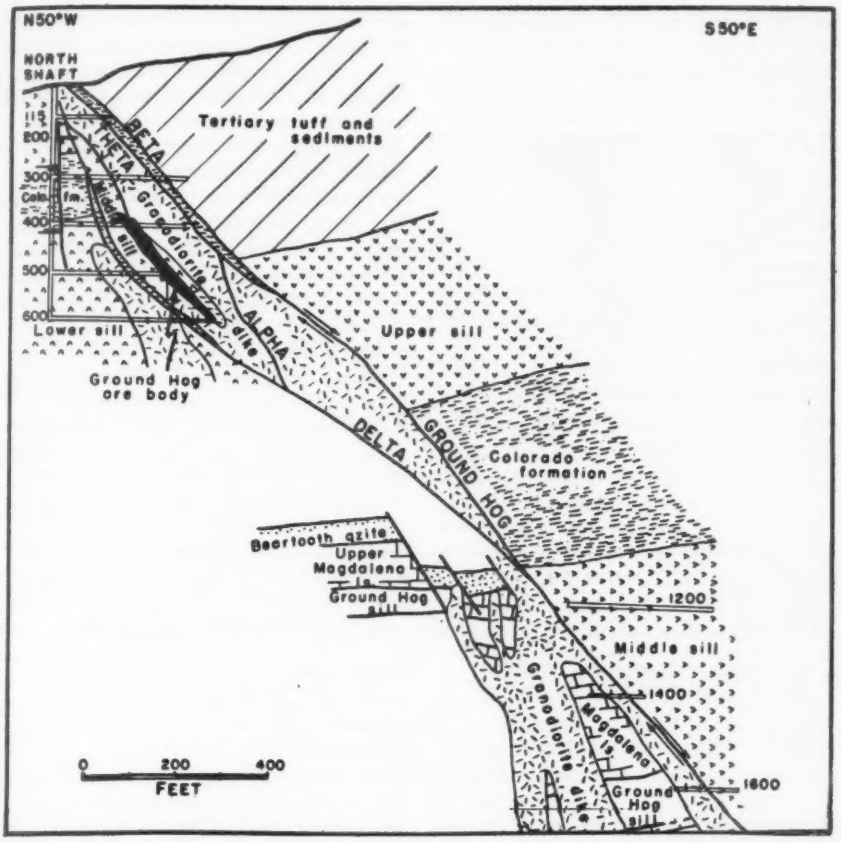


FIGURE 10.—GENERAL CROSS SECTION, UPPER PORTION OF THE GROUND HOG MINE

are due primarily to variations in the relative grain size.

In the Hanover area the equigranular phenocrysts are about 80 per cent feldspar, 15 per cent hornblende, and 5 per cent biotite. Clearly reflecting white laths of plagioclase and lustrous dark-green hornblende prisms average 5 mm. long. Biotite forms dull-green hexagonal columns 3–4 mm. wide, with the c-axis commonly two to three times the a and b-axes. Typically green epidote is usually present as bladed crystals or masses. Small pyrite crystals and round grains of glassy quartz about 1 mm. in diameter are common. Sphene is an accessory mineral observed in thin sections and in some instances crystals attain sufficient size to be recognized in hand specimens.

Exposure of dikes of this type may be observed on level 4 of the Empire Zinc mine at N3690-E6370, and in the Oswaldo mine along the E436N cross-cut between survey stations 504 and 505 (Fig. 11). In some places hornblende is the most abundant phenocryst and gives the rock a felted appearance. A dike of this type is exposed 500 feet north of the Republic No. 1 shaft.

The workings of the Republic No. 1 mine and the Oswaldo mine follow the Gamma dike zone (Pl. 10), where not only hornblende granodiorite porphyry dikes but other types as well are found (Fig. 12).

At the Ground Hog mine, hornblende porphyry is a speckled rock marked by white rectangular feldspar grains 6–8 mm. long set in a dark-grey groundmass. The feldspar phenocrysts constitute about 50 per cent of the rock (Pl. 3, fig. 3).

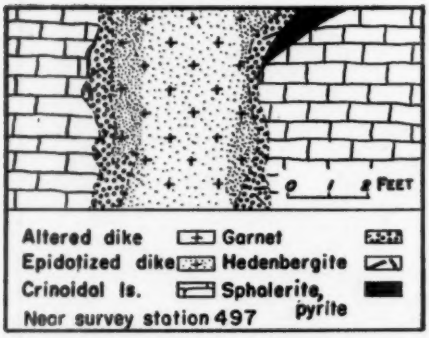


FIGURE 11.—PRE-ORE DIKE, E436N, CROSS CUT OSWALDO MINE

Ordinarily in this dike rock, the ratio of feldspar to ferro-magnesian constituents varies considerably. Feldspar is andesine or orthoclase. Zoned rectangular laths of andesine are abundant. They average 4–5 mm. long. Orthoclase phenocrysts of similar size are present in small quantities. In some specimens orthoclase occurs as irregular patches within plagioclase grains. In specimens where hornblende is abundant, it occurs in grains of many sizes, ranging from large phenocrysts to tiny needles incorporated in the groundmass; the resulting felted texture is characteristic. Biotite forms rectangular sections which are usually altered to chlorite and epidote, even where the hornblende and feldspars are fresh.

Pyrite is common as grains or irregular masses surrounding earlier-formed crystals of feldspar and hornblende. It is of late introduction. Magnetite is found in many specimens, and where relations can be observed it too seems to be younger than the rock-forming silicates. Magnetite stringers cut hornblende porphyry in the Ground Hog mine. Magnetite and pyrite occur together in a few of the slides examined, but the age relation could not be established. Among the minor constitutents are small clear rounded quartz grains less than 1 mm. in diameter, apatite prisms up to 1.5 mm. long, and rhombic sphene crystals of similar size. Apatite and sphene usually occur together.

The groundmass of fresh hornblende porphyry is fine-grained and difficult to resolve even under high magnifications. The main component is apparently quartz. In most specimens the groundmass is obscured by sericite, chlorite, and montmorillonite.

Quartz granodiorite porphyry.—Quartz porphry dikes, like hornblende porphyry dikes, follow major fault lines, usually trending north, in the Hanover area, northeast between the Ivanhoe and Ground Hog shafts. A large quartz porphyry dike cutting the Santa Rita stock strikes north to N30°W, in keeping with local structure. Many granodiorite porphyry dikes, such as the one near the Ivanhoe shaft, are composite in character and contain both hornblende porphyry and quartz porphyry. The Oswaldo mine, furnishes an interesting example of this type (Fig. 12). A central core of quartz porphyry is sheathed on both walls by hornblende porphyry. Diamond drilling shows that this relationship persists for 250 feet along strike of the dike.

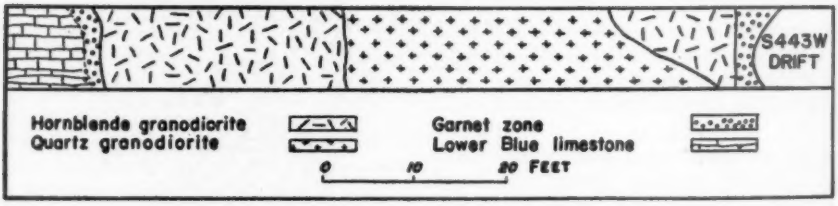


FIGURE 12.—COMPOSITE DIKE, OSWALDO MINE

At Santa Rita quartz porphyry dikes were emplaced within the stock along a zone of fractures that parallels the aplitic zones and the alteration axis of the stock in the North Pit.

This parallelism continues through the Central Island. In the South Pit there is a marked divergence of 45° between the trend of the principal quartz porphyry dike zone and the alteration axis of the intrusive.

This principal quartz porphyry zone, consisting of distinct and branching member dikes which may be traced for 600 feet, is generally 100–300 feet wide but may attain a width of 400 feet as in the Central Island. It has the north-south regional trend of similar dikes elsewhere in the Santa Rita-Hanover-Ground Hog area. The strike changes from N30°–55°W in the North Pit and Central Island to North, N20°E, briefly N45°E, in the South Pit. Other minor quartz porphyry dikes occur within the Santa Rita intrusive and the surrounding sills and sedimentary rocks.

The quartz porphyry dikes which cut the intrusive are not only irregularly braided and branching along their strike but show considerable variation vertically. The dip is generally steep or vertical. Only rarely are low-angle attitudes observed. The inclined dikes found seem to be the result of local branching and widening.

The quartz porphyry dikes show well-developed vertical jointing and less prominent cross fractures. The vertical joints furnished avenues for deposition of limonite, kaolinite, quartz, and secondary pyrite by ground waters. Supergene solutions penetrated the Santa Rita. intrusive to great depths along the fractures. The dikes are everywhere iron-stained showing the effects of ground water circulation and leaching down to the 5900 Bench of the South Pit. The discolored dikes stand out in marked contrast to the gray granodiorite porphyry in the lower benches of the pit (Pl. 5, fig. 2; Pl. 6, fig. 2).

The term "quartz porphyry" includes a group of rocks of variable appearance. Thin sections reveal that differences are due more to variation in texture than to changes in mineral content. The quartz porphyry dikes at the Ground Hog mine and at Santa Rita are similar. The phenocrysts are of corresponding size but they constitute a larger portion of the rock at Santa Rita giving a more granitic texture. Near Hanover the quartz porphyry varies from a medium-grained gray rock to a fine-grained light-colored variety which may be confused with the younger latite dikes.

In a typical specimen of quartz porphyry, phenocrysts comprise about 60 per cent of the rock, the remainder being a dense groundmass often too fine-grained for resolution under the microscope (Pl. 4, figs. 1, 2, 3). Feldspar constitutes about 65 per cent of the phenocrysts, quartz 20 per cent, and ferromagnesian minerals 15 per cent, biotite exceeding hornblende.

The feldspar is of two types. Orthoclase crystals up to 11 mm. long are scattered through the mass and contain inclusions of chlorite, apparently replacing some ferromagnesian mineral. The plagioclase is andesine but according to the maximum symmetrical extinction angle on albite twins, the plagioclase in these quartz porphyry rocks is slightly more sodic than the plagioclase of the hornblende porphyry.

Numerous rounded, embayed quartz phenocrysts up to 2.5 mm. in diameter appear throughout the rock. Many quartz grains are surrounded by a rim of secondary quartz containing specks of the groundmass (Pl. 4, fig. 3). The rim is in optical orientation with the nucleus. The ferromagnesian minerals have been completely altered and are identified only by the configuration of their pseudomorphs. Chlorite and epidote are the alteration products. Replacement of original biotite followed the biotite structure giving chlorite fibers with parallel extinction.

Pyrite is common, forming small irregular masses usually along boundaries of rock-forming silicates. Magnetite and pyrite are of late introduction and one specimen shows rims of pyrite around magnetite, indicating that pyrite is later. Rhombs of sphene and prisms of apatite are monor constitutents. The groundmass is fine-grained and dusty with alteration minerals, flakes of sericite, chlorite, epidote, and carbonate. Many specimens show the effects of silicification.

Quartz porphyry is similar petrographically to hornblende porphyry but the rocks can be distinguished by the following characteristics:

Quartz porphyry	Hornblende porphyry
(1) Quartz phenocrysts up to several mm. in diameter are abundant.	(1) Quartz phenocrysts are sparse and seldom exceed 1 mm. in diameter.

(2) Large pink poikilitic orthoclase porphyroblasts are characteristic.	(2) Orthoclase porphyroblasts are absent.
(3) The most abundant dark mineral is biotite.	(3) The most abundant dark mineral is hornblende.
(4) Small allanite grains may be present.	(4) Allanite is absent.
(5) The rock is medium- to fine-grained.	(5) The rock is medium- to coarse-grained.
(6) As a rule the texture is markedly porphyritic.	(6) The texture is porphyritic to granitic.

Alteration, so pronounced in the granodiorite porphyry of the Santa Rita intrusive, has also affected the younger quartz porphyry dikes. Columnar hydromica and chlorite pseudomorphs are commonly found after biotite. Feldspars are generally altered to kaolinite and montmorillonite. The dike rock frequently appears bleached.

Textural variations occur not only from bench to bench, along the strike of these dikes, but also within a single exposure where chilled contacts occur. Composite dikes characteristic of the Hanover and Oswaldo mines were observed within the pit at Santa Rita. Some grouping, however, occurs along the southwestern rim of the pit.

Latite.—Spencer and Paige (1935, p. 41) and Lasky (1936a, p. 45) have classified the dike rocks of Tertiary age as latite. Lasky believes that the dikes are genetically related to the Tertiary lavas and suggests that dikes may have served as feeders for the flows.

A latite dike cuts the down-flaulted block of Tertiary gravels south of Hanover. Immediately northeast, the large latite mass in Bull Hill also cuts the gravels. Dikes of similar petrology occur elsewhere on the surface, in the Santa Rita pit, and underground in the Empire Zinc mine. The usual trend of the latite dikes is easterly, cross-cutting the structural pattern of earlier granodiorite porphyry dikes. For example, on the Central Island at Santa Rita a latite dike having an easterly strike intersects a north-trending quartz porphyry dike. The latite dikes therefore represent a later fracture system superimposed upon the earlier regional structure.

Megascopically, latite is a gray porphyritic rock with white feldspar phenocrysts and spangles of shiny biotite in a dark-gray fine-grained groundmass. Quartz is present in some specimens. Biotite occurs as columnar prisms in the dike cutting Tertiary gravels south of Hanover, but in other dikes thin hexagonal flakes are characteristic. Biotite is most common in the center of the dikes and is usually lacking in the marginal zone. Trachytic flow structure is common along dike borders.

The feldspar consists of oligoclase-andesine and variable amounts of orthoclase. Individual rectangular phenocrysts are present but not common; generally several feldspar grains form a cluster 3 or 4 mm. in diameter. Feldspar forms about a third of the rock. Biotite occurs as brown pleochroic rectangles up to 1.5 mm. wide (Pl. 4, fig. 4). Most biotite is fresh and is a distinctive constituent of the rock. The accessory minerals include small widely-distributed magnetite grains and minor quantities of apatite and sphene. In fresh latite the groundmass consists almost entirely of small plagioclase laths about .05 mm. long. The laths are aligned in a sub-parallel flow structure around phenocrysts. Quartz is a minor constituent not present in all thin sections.

Latite dikes have not altered as much as the older rocks. Calcite is rather common. It partly replaces phenocrysts of feldspar and biotite and forms stringers or irregular areas in the groundmass. In many specimens, stringers and eyes of secondary silica cut the groundmass. Biotite may be partly replaced by muscovite, and the plagioclase may contain minor sericite. No epidote has been observed.

Dikes of fine-grained quartz porphyry in the Empire Zinc and Oswaldo mines are similar to latite dikes, and distinction between the two rocks may be difficult. In some cases the name "latite" has been inappropriately applied to fine-grained post-ore granodiorite porphyry. Latite is characterized by the following megascopic features:

1. Lustrous, black biotite flakes.
2. Marginal trachytic flow texture.
3. Dark-gray color, usually darker than fine-grained quartz porphyry.
4. General absence of the quartz phenocrysts which are characteristic of quartz porphyry.

No latite dikes were observed in the Oswaldo mine. Typical latite is exposed on the 4th level of the Empire Zinc mine in localities having co-ordinates: N3550, E6400; N4080, E7060; N3950, E7500; N4950, E5750; N3830, E6375.

Age relationships of granodiorite porphyry dikes.—The grandodiorite stocks and the granodiorite dikes are closely related both petrographically and genetically, although in detail the three rocks appear to be of slightly different ages. It is certain from structural evidence that the quartz porphyry dikes are later than both the stocks and the hornblende porphyry dikes. Several quartz porphyry dikes cut the Santa Rita stock (Pl. 5, fig. 2; Pl. 6, fig. 2) and north of the Republic No. 1 shaft a quartz porphyry dike can be traced for some distance into the Hanover stock. Other granodiorite porphyry dikes which cut the stock are mapped by Spencer and Paige (1933, Pl. 1). Quartz porphyry dikes cut hornblende porphyry dikes in the Ground Hog and Oswaldo mines.

The age relationship between hornblende porphyry dikes and the stocks cannot be determined so readily. Hornblende porphyry dikes are lacking near the Santa Rita stock. At Hanover cover makes it impossible to establish the relations between the stock and the dikes. Conclusions as to age relations must be based on microscopic and chemical data.

Hornblende porphyry consists principally of hornblende and andesine, both of which crystallized early from the granodioritic magma. Quartz, orthoclase, and biotite, all late minerals, are present only in small quantities. In contrast, the stock rock contains appreciable quartz, orthoclase, and biotite. Furthermore the andesine (Ab_{58}) is more sodic than andesine of the hornblende porphyry diorite (Ab_{53}). Thus the mineral content suggests that the hornblende porphyry dikes are earlier than the stock.

Analyses of the Hanover stock, quartz porphyry, and hornblende porphyry are shown (Table 1) and the norm of each rock (Table 2). The Hanover granodiorite contains more SiO_2, K_2O, and Na_2O than the hornblende porphyry and less CaO, MgO, and Fe_2O_3. Since the composition of a magma usually changes with time, becoming enriched in silica and alkalis, the analyses suggest that the stock-rock is later than the hornblende porphyry. This may account for the absence of hornblende porphyry dikes in the Hanover stock other than along margins.

In Figure 13 the same analyses are plotted against relative age of the rocks. Since it is not definitely known whether the hornblende porphyry is older or younger than the stock-rock, two age-composition curves are presented. Graph A represents hornblende granodiorite as older than the stock-rock; in graph B these relations are reversed. In graph A, CaO, MgO, total iron and total alkalis show a progressive change with age, as would be expected under normal differentiation. In graph B, the curves are irregular, and no oxide shows a progressive change with age. Of the two graphs, A shows the more consistent variation on composition, suggesting that hornblende porphyry is the oldest rock.

TABLE 1.—ANALYSES OF IGNEOUS ROCKS
(Silve Kallmann, Analyst)

	(1)	(2)	(3)
SiO_2	56.68	61.26	60.72
Al_2O_3	16.18	16.22	16.05
Fe_2O_3	3.50	3.00	3.07
FeO	2.25	2.38	1.42
MnO	0.21	0.08	0 17
MgO	3.25	2.57	1.53
CaO	7.82	6.12	4.46
Na_2O	2.55	4.34	2.59
K_2O	1.92	2.61	4.93
H_2O plus	1.15	0.20	1.07
H_2O minus	0.60	0.15	0.27
CO_2	1.40	0.09	1.71
TiO_2	0.60	0.52	0.32
P_2O_5	0.48	0.48	0.23
S	1.18	0.05	1.65
	99.77	100.07	100.19

(1) Hornblende porphyry from Empire Zinc and Oswaldo mines.
(2) Hanover granodiorite from Empire Zinc mine.
(3) Quartz porphyry from Oswaldo mine.

STRUCTURAL FEATURES

General description

The present structure is largely a product of deformation during intrusion of the two por-

phyry stocks, and subsequent faulting. The area between the Ground Hog mine and Wimsattville, 2.5 miles northeast, lies largely beyond the zone affected by intrusion and faulting of

TABLE 2.—NORMS OF IGNEOUS ROCKS

	(1)	(2)	(3)
Quartz	18.2	13.9	20.8
Orthoclase	11.1	15.6	28.9
Albite	22.0	36.2	22.0
Anorthite	26.1	17.2	11.4
Corundum*	0.3	—	2.4
Diopside	—	3.0	—
Hypersthene	8.0	5.8	3.8
Magnetite	1.9	4.4	—
Hematite	1.4	—	3.0
Ilmenite	1.2	0.9	—
Pyrite	1.7	0.1	1.7
Apatite	1.3	1.3	—
Rutile	—	—	0.8
Calcite	3.2	2.0	3.9
Excess sulphur	—	—	0.5
Water	1.8	0.4	1.3

(1) Hornblende porphyry from Empire Zinc and Oswaldo mines.
(2) Hanover granodiorite from Empire Zinc mine.
(3) Quartz porphyry from Oswaldo mine.
* Excess Al_2O_3 which is calculated as corundum probably represents sericitic alteration of the feldspars.

the normal type is usually dominant. Near the Hanover and Santa Rita stocks, the structure has been developed largely by intrusive action and complicated by faulting. The nearly horizontal attitude of Paleozoic strata over wide areas suggests that before faulting and intrusion the structure was comparatively simple.

Faulting

Most faults are of the high-angle normal type. Major fault zones comprise a network of coalescing sub-parallel faults which form a series of fault blocks and slivers. Fracture planes have been filled in whole or in part by from one to three generations of dikes. This is well illustrated in the area of linked faults and dikes between the Ground Hog mine and Wimsattville. Here the major structure is the Ivanhoe-Lovers Lane fault which strikes northeast and dips southeast. At the surface, the Middle sill of the Colorado formation is faulted against the Upper sill. Northeast of the Ivanhoe shaft, the Ivanhoe-Lovers Lane fault is joined from the west by the Copper Glance fault,

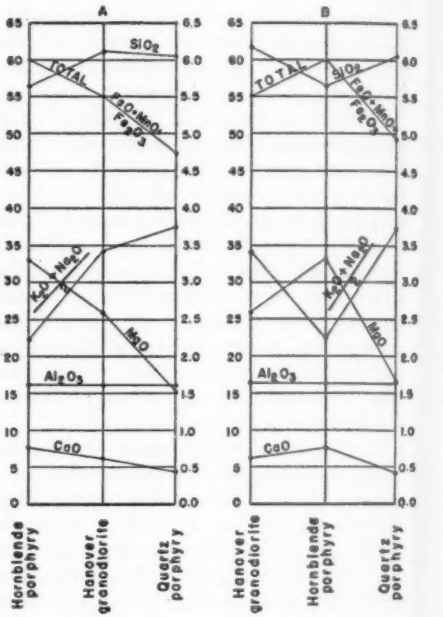


FIGURE 13.—VARIATION OF CHEMICAL ANALYSIS WITH ROCK TYPE

the combined displacement being about 1600 feet.

Faults near Hanover have a general northerly trend but tend to radiate away from the Hanover stock at right angles to its margin. The faults dip steeply to the west in contrast to those farther south which are inclined easterly. Displacements are to the west and do not exceed several hundred feet. The fault planes have served as channels for emplacement of granodiorite porphyry dikes and for the introduction of solutions which formed ore bodies through replacement of favorable limestone beds.

The different periods of movement are not too clearly defined, although the main faulting originated after the intrusion of the upper Cretaceous quartz diorite sills which the faults displace. Granodiorite porphyry dikes closely

related in age to the granodiorite stocks follow fault lines which in some instances must have existed prior to their emplacement. However, the interval of time is not known.

Movement has been repeated a number of times. Granodiorite porphyry dikes which themselves follow fault lines have been fractured to permit entry of ore solutions, and in some places the fractures were healed by a later group of post-ore granodiorite porphyry dikes. Sedimentary rocks along the Psi fault of the Empire Zinc Company mine have been displaced more than early pre-ore granodiorite porphyry dikes, which are displaced more than later post-ore granodiorite porphyry dikes. Here at least three periods of movement are indicated: one after intrusion of the sills and before intrusion of the early granodiorite porphyry dikes, a second approximately contemporaneous with ore deposition and before the later granodiorite porphyry dikes, and a third post volcanic. These may be correlated with the three periods of faulting recognized by Lasky (1936a, p. 49) in the Bayard area: one after the Cretaceous sills and before the granodiorite porphyry dikes; a second after the granodiorite porphyry dikes (no distinction is made between earlier and later dikes), and a third after expulsion of the Tertiary volcanics.

Faults of Tertiary age are found in several places. Immediately northwest of Wimsattville, a graben of Tertiary gravels is surrounded by an area of older sedimentary rocks. Tertiary movement is recorded in the Santa Rita open pit by minor offsets in a Tertiary latite dike. The lavas south of Santa Rita are faulted in a considerable number of places.

Deformation Due to Igneous Intrusion

In the vicinity of Hanover and Santa Rita, the major structures are those imposed upon the sedimentary rocks by intrusion of the granodiorite porphyry stocks. Intrusion of the Hanover stock apparently produced more intense deformation than intrusion of the Santa Rita stock.

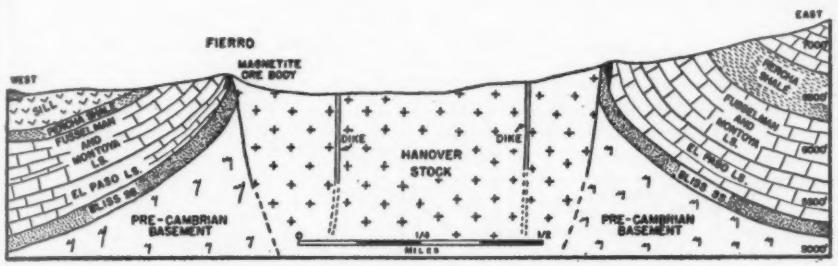


FIGURE 14.—CROSS SECTION THROUGH HANOVER STOCK

Lower Paleozoic rocks exposed along the eastern and western margins of the Hanover stock dip steeply away from the stock on all sides (Fig. 14); the dip on the east is nearly vertical. Younger formations are less steeply inclined, and the steepness of dip decreases outward from the stock. Exploration at the southern end shows that the edge of the granodiorite body is floored by sedimentary rocks. Lateral pressure exerted by the overriding stock developed an overturned syncline adjacent to the igneous mass and an asymmetrical anticline beyond. The folds parallel the edge of the granodiorite. At the Pewabic mine (Schmitt, 1939, p. 786), folding was so intense that thrusting took place along a low-angle fault plane. In the Empire Zinc Company mine, overturning is suggested (Fig. 15), but there is no evidence of a thrust. Exploration indicates that the folding, most intense at the surface, decreases with depth. Along the axis of the asymmetrical anticline parallel to the southern edge of the stock (Fig. 19; Pl. 10), lower Mississippian rocks are brought to the surface; these are the oldest formations exposed in the Santa Rita-Hanover-Ground Hog area.

The Santa Rita stock arched and cut through overlying sedimentary rocks and quartz diorite sills. Beds on all sides of the stock dip away

from the center at angles of 10°–55°. The steep dips common at Hanover have not been observed. The long axis of the Santa Rita stock extends slightly west of north, approximately

tense jointing and fracturing may be observed in the granodiorite porphyry, but adequate analysis would be a separate problem. In general, however, a distinct northerly trend is

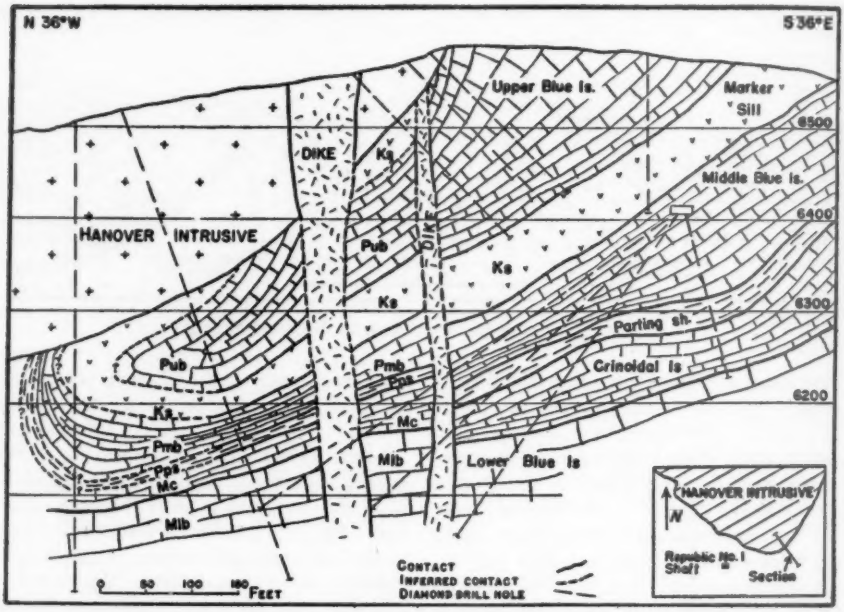


FIGURE 15.—SECTION EAST OF REPUBLIC NO. 1 SHAFT OF EMPIRE ZINC COMPANY

in line with the northward-trending longitudinal axis of the Hanover mass. Structural alignment, petrographic similarity, and deformation of rocks of corresponding age suggest that the two stocks are derived from a common parent magma. The smaller area of the Santa Rita stock, the more intense mineralization and alteration of the granodiorite porphyry, the more extensive alteration of the country rock, and the younger age of bordering formations at the surface, all indicate that the Santa Rita stock has been less eroded than the Hanover body.

Structure in the Santa Rita Intrusive

Two kinds of geologic structures are apparent in the immediate vicinity of the Santa Rita stock: those resulting from igneous intrusion, and those representing minor faulting which subsequently modified the primary structures. Inapparent, particularly in chalcocite-bearing fractures.

In Cretaceous time or later, the Santa Rita granodiorite porphyry rose to its present position and formed a cross-cutting mass beneath uparched sedimentary rocks and sills of Carboniferous to Upper Cretaceous age (Fig. 16). The marginal sedimentary rocks and sills dip away from the stock at angles varying from 10° to 55° (Fig. 17).

Injection of the quartz porphyry and latite porphyry dikes took place along prominent fracture systems at two distinct periods after the intrusive had solidified. The early north-south dikes and aplitic zones occupied post-magmatic tensional fractures parallel to the axis of the intrusive. A later period of fracturing within the intrusive at right angles to the intrusive axis provided openings for the emplacement of the latite porphyry.

Normal faulting of the marginal, metamor-

phosed sills and the sedimentary rocks within the Santa Rita area is of secondary structural importance. Most faults appear to be post-magmatic and of probable Tertiary age. It seems likely that they were produced by a relaxation of the compressional stresses that accompanied the period of Laramide igneous intrusion.

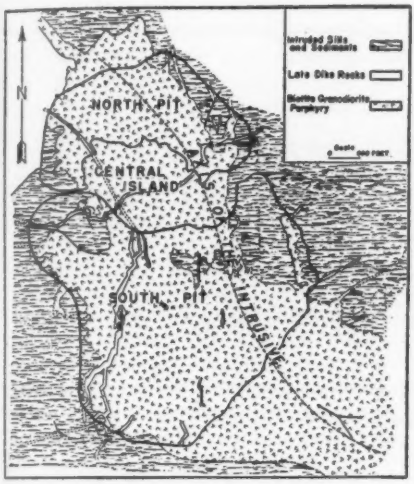


FIGURE 16.—GENERAL OUTLINE, SANTA RITA INTRUSIVE

The Carbonate fault striking N65°E may be traced across Lee Hill for 1400 feet between waste dumps. It may continue northeastward beneath waste into the North Pit. On Lee Hill the upper quartz diorite porphyry sill has been faulted down against the lower middle sill along a 10–40-foot, iron-stained breccia zone shown to have a southeast dip of 70° in the flux quarry (Pl. 7, fig. 1). Slickensides indicate vertical movement. In the North Pit, the Syrena formation has been brought into contact with the lower Cretaceous sedimentary rocks. This is possibly a continuation of the Carbonate fault.

Another major fault marks the contact of the metamorphosed sedimentary rocks with the middle sill and altered granodiorite porphyry on the west wall of the South Pit. It appears beneath the waste dump along U. S. Highway No. 180. In the best exposures of the upper benches, the Colorado and Beartooth quartzites are separated from the down-thrown middle quartz diorite porphyry sill by a zone of limonite-stained gouge measuring as much as 2 feet wide (Pl. 7, fig. 2). The fault disappears beneath fill in the lower benches of the west wall but it is believed to continue along the Syrena-granodiorite porphyry contact to the bottom of the South Pit. Slickensides at the margins of the gouge zone indicate vertical displacement.

On the north wall of the North Pit, the Romero fault (Spencer and Paige, 1935, p. 55) striking N27°E brings the Syrena formation into contact with the Beartooth quartzite. This fault cuts through and offsets a stringer of hydromica granodiorite porphyry.

Other minor normal faults with high angles appear in the sedimentary rocks and sills of the Santa Rita area. The latite porphyry dike is repeated by a fault along the upper benches of the north wall of the South Pit. In lower

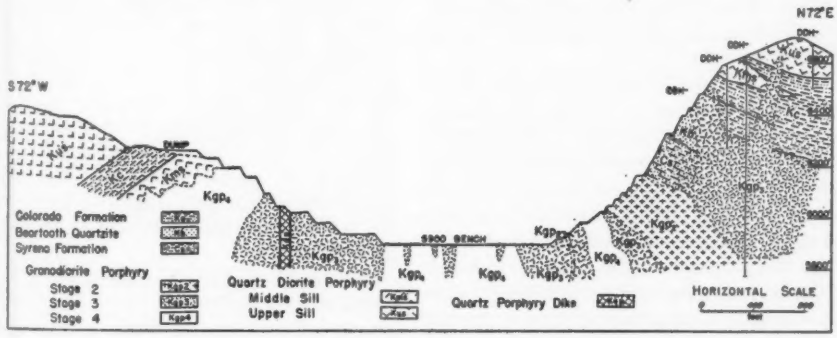


FIGURE 17.—GENERALIZED CROSS SECTION, SOUTH PIT, SANTA RITA

benches beneath this fault, northwest-inclined, magnetite, pyrite-replaced beds within the Syrena formation are repeated by two parallel faults 100 feet apart. Another minor fault brings the middle sill into contact with the

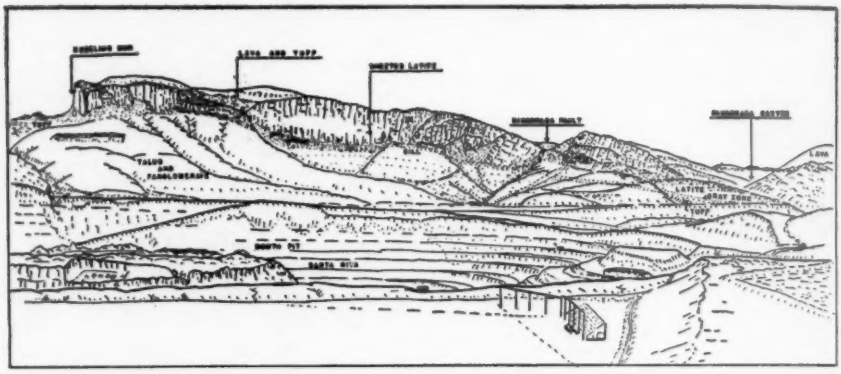


FIGURE 18.—TERTIARY LAVAS SOUTH AND EAST OF SOUTH PIT

altered granodiorite porphyry in the leached zone directly below the Chino switch on the southwest wall of the South Pit (Pl. 6, fig. 1). Occasional faults cut sedimentary rocks, sills, and dikes in the hills on either side of the Santa Rita intrusive.

There is faulting in the hills south and east of the South Pit (Fig. 18). 1. Colorado sills and sedimentary rocks offset along northeast-trending apophyses of hydromica granodiorite porphyry suggest faulting at the time of the eruption of the Santa Rita stock. 2. One prominent fault of northeast orientation occurs in the East-West Tunnel at the cross-cut near the east end. 3. The east wall of the South Pit, near the so-called Niagara fault, is difficult to work since blasting in the lower benches may readily release great masses of rock near the pit rim several hundred feet above. 4. Spencer and Paige (1935, Pl. 1) suggest that the occurrence of large blocks of rhyolitic tuff along the east rim of the South Pit represent landslide debris carried down from the flanks of the Kneeling Nun hill. Lack of displacement of the tuff in Niagara Gulch indicates that the landslide debris may hardly be attributed to the Niagara fault. If the fault exists it is presumably entirely pre-Tertiary. On the other hand, the Rinconada fault (Fig. 18) is a definite Tertiary and quite likely also a pre-Tertiary structure.

The Niagara fault might pass westward through the South Pit to continue as the fault forming the contact between the sedimentary and the igneous rocks in the west wall. However the Niagara fault could not be traced through the altered granodiorite porphyry of the stock. The granodiorite porphyry sedimentary boundary of the east wall of the South Pit, appears as a simple igneous contact with the intruded formations. There is no displacement of the principal quartz porphyry dike, that should be cut if such a fault existed. Further alteration and fracturing of the granodiorite porphyry has been so intense throughout the 5900 Bench, where this fault would be projected, that evidence of brecciation would be questionable.

North-south faulting is observable in the tunnel beneath the hills east of the South Pit, but the existence of the Niagara fault as a major cross structure is open to question.

MINERAL DEPOSITS

Types of Mineral deposits

Four types of mineral deposits have been exploited in the area:

1. Contact metamorphic magnetite deposits.
2. Zinc ore bodies formed by replacement of favorable limestone beds.
3. Zinc ore filling fissures in a fault zone.
4. Copper mineralization associated with the Santa Rita stock.

Magnetite Bodies

Masses of magnetite formed by contact metamorphism exist in the limestones adjacent to the Hanover stock (Fig. 14) and, to a lesser extent, around the Santa Rita stock. Near the Hanover intrusive, the bodies are lens-shaped with long axes parallel to the border of the intrusive. The most extensive magnetite deposits have been found near Fierro, 2 miles north of Hanover. Here the host rock is the series of Ordovician and Silurian limestones called locally the "lower limestones." The principal gangue minerals are serpentine and wollastonite. Open-pit operations at Fierro were extensive but are now abandoned.

Similar magnetite bodies occur in Carboniferous limestones (the "upper limestones") at the south end of the Hanover stock near the town of Hanover. The deposits are confined for the most part to a narrow zone paralleling the intrusive contact, but magnetite deposition may also extend outward into the limestones along faults and dikes. The principal gangue mineral is garnet.

Magnetite deposition near the Santa Rita stock is less extensive. In an area extending northward from the North Pit, the soil is red and contains abundant magnetite nodules. Numerous pits indicate the sites of exploration. This zone coincides with the structural axis of the Santa Rita stock, and it may represent the effect of contact metamorphism on rocks lying above a subsurface projection of the intrusive. Magnetite occurs within the metamorphosed Syrena formation on the edges of the South Pit.

Away from the two stocks, magnetite is widely scattered. It occurs as an accessory mineral in all the igneous rocks, and lenses of magnetite occur locally within the sedimentary rocks. At some places, for example on the southern end of the Oswaldo property, magnetite is developed at the surface adjacent to zinc-bearing structures. Hence the occurrence of magnetite may have value as a guide to mineralization.

Zinc Replacement Deposits

Bodies of zinc ore have been formed where favorable limestone beds have been exposed to zinc-bearing solutions. The principal ore horizon at the Empire Zinc and Oswaldo mines is the Crinoidal limestone. Production of replacement ore in the Ground Hog mine has been from both the Crinoidal and Upper Magdalena limestones.

For the most part replacement of the limestones has taken place along faults and pre-ore dikes, and ore bodies usually occur adjacent to such structures. As suggested by the distribution of mine workings (Fig. 19), much of the production in the Empire Zinc mine has come from ore bodies adjacent to the Gamma, Eta, Annie Fox, and Theta fault zones. Northwest of No. 7 shaft, however, early mining followed blanket ore developed in the Crinoidal limestone along the anticline paralleling the stock contact. Near-surface ore is being mined here by open cuts. In the Oswaldo mine, ore occurs along the southward continuation of the Gamma zone, as well as along parallel structures to the east. Ore bodies in lower levels of the Ground Hog mine are localized along pre-ore dikes.

Sphalerite and galena are the principal ore minerals, in a gangue of andradite, hedenbergite, and ilvaite. Schmitt (1933, p. 198) has described the deposits in detail and notes that galena is concentrated along the outer edge of the ore bodies. As a rule, an ore body lies between a wall of unaltered limestone and a wall of silicate gangue minerals (Fig. 20). The adjacent dike is usually epidotized. In a few places the contact silicate zone is lacking and the dike itself is mineralized, sphalerite occurring in an epidote gangue.

Zones of movement can be recognized within many dikes. Adjacent to such a zone the dike is strongly epidotized. If the fracture is near one wall of the dike, the adjacent limestone may be more strongly metamorphosed along that wall than along the opposite wall (Fig. 21). Apparently the ore solutions did not originate with the dike but were introduced later and followed shear zones. The detailed sequence is:

1. Emplacement of pre-ore dikes.
2. Deformation of pre-ore dikes.
3. Introduction of ore solutions.
4. Emplacement of post-ore dikes.

Fissure-Filling Deposits of Zinc Ore

Mineralization in the upper levels of the Ground Hog mine has been described by Lasky

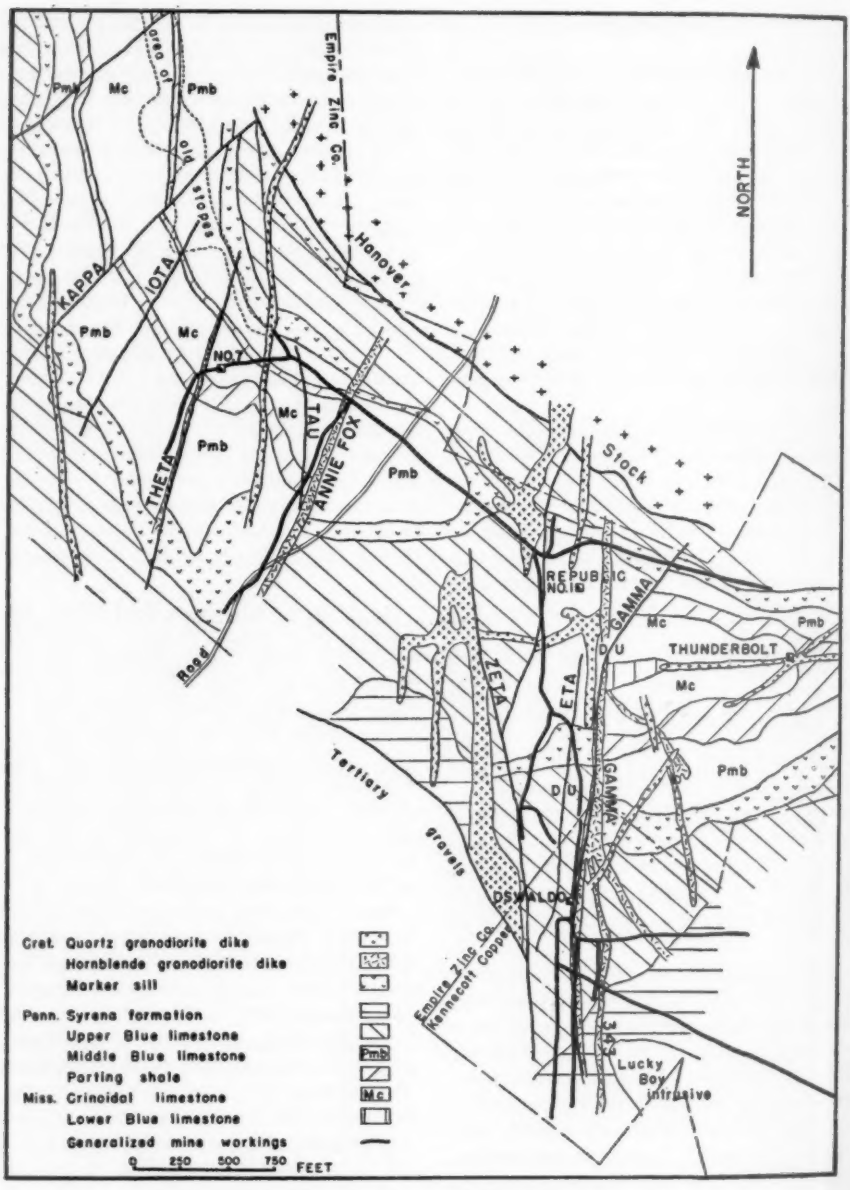


FIGURE 19.—GEOLOGIC MAP OF EMPIRE—OSWALDO AREA

(1936a, p. 110). The Ground Hog ore body is spoon-shaped and lies in the vicinity of the Beta-Theta (Ground Hog) fault zone (Fig. 10). The ore minerals are sphalerite, galena, chalcopyrite, and pyrite in a gangue of quartz and calcite.

Disseminated Copper Deposits

In the Santa Rita stock, chalcocite occurs in veinlets as a coating on pyrite and as a replacement of pyrite. The copper content is low

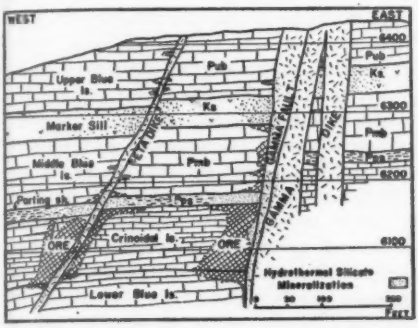


FIGURE 20.—GENERALIZED DIAGRAM OF ORE OCCURRENCES ALONG THE GAMMA AND ETA DIKES, EMPIRE ZINC MINE

upward. Pyrite generally occurs disseminated in the form of euhedral cubes and pyritohedra or as irregular grains, but veins and fissure fillings measuring up to several inches wide are common.

Magnetite was probably the earliest iron mineral to crystallize, during the closing stages of magmatic intrusion. Some of the pyrite was probably contemporaneous, but most of it formed later. The magnetite occurs as irregular grains disseminated through the least altered granodiorite porphyry. It also partially replaces the more calcareous beds of the highly metamorphosed Syrena formation along the contact with the intrusive. Magnetite is the cementing material in the Whim Hill breccia. Veins of magnetite in the sedimentary series at the east end of the South Pit are closely allied to the pyrite stringers that cut through them in places.

In the area north of the North Pit where the limestone formations lie along the surface, considerable accumulations of magnetite have been

FIGURE 21.—FRACTURE ZONE IN GAMMA DIKE, OSWALDO MINE

in grade but the mineralization is widespread. Oxidation had produced malachite, azurite, cuprite, native copper, melaconite, chrysocolla, and chalcanthite.

METALLIC MINERAL ASSOCIATION

Iron

Pyrite is the most widespread of the hypogene iron minerals. It occurs in the sedimentary and sill rocks bordering the intrusive, in the igneous rocks of the stock, and in the associated dikes. Pyritiferous beds and zones are especially prominent in the Syrena formation close to the ore body. Pyrite-bearing zones follow fractures upward into Cretaceous quartzitic sedimentary rocks. These zones taper toward the surface suggesting deposition by solutions migrating

found. A number of these have been large enough to lead to quarrying operations. In the early summer before the usual rainy season begins, the magnetite-bearing zone may be traced and even photographed by the deep-brown coloration in the soil. The area, in which the magnetite pits are most abundant and magnetite pebbles are common in the surface soil; lies along a continuation of the axis of the Santa Rita intrusive. It is elongated in the direction of the Hanover intrusive. This may be a surface indication of the northward extension of the Santa Rita intrusive beneath the limestone.

Hematite occurs in the oxidized zone, in veins and within a highly fractured mass in the Syrena formation near the intrusive contact at the base of the north wall of the South Pit. This

fractured and recemented hematite body on the north wall of the South Pit occurs on the banks of the two lowest benches for a distance of 400 feet. The hematite in a fresh exposure is fine-grained, compact, and red-brown. It is cut by intricate networks of quartz, kaolinite, pyrite, and chalcocite veins with secondary malachite staining the clay. The hematite weathers to a red-violet powder that may be traced into adjoining highly silicified granodiorite porphyry. The intricate veins are obscured in the weathered, iron-stained exposures. The irregular outline of this deposit suggests early replacement of the sedimentary rocks by iron oxide. Later fracturing of the mass, probably contemporaneous with the formation of cracks in the granodiorite porphyry, was followed by the introduction of silica, clay, and sulphides.

Limonitic material is ubiquitous and appears to be derived from pyrite, magnetite, and iron-bearing silicates. It occurs in all sedimentary and igneous rocks. The least altered granodiorite porphyry is largely free from limonite, but the hydrous iron oxide aggregate becomes more abundant as the weathering of the granodiorite porphyry increases. It is especially abundant in near-surface oxidized areas. Limonite imparts the reddish brown to maroon color to the irregular, iron-stained, oxidized zones found throughout the North Pit and in the upper benches of the South Pit. The material, probably largely goethite, is found not only as stains; but as dense, irregular masses; in massive veins and fissure fillings; and as pseudomorphs after pyrite.

Siderite occurs to a limited degree in the capping where it is found intimately associated with the hydrous carbonates of copper.

Copper

Chalcocite, the principal copper ore mineral, is found most abundantly as disseminated, irregular grains. Scattered chalcocite veins and fissure fillings, measuring several inches in width, may be found throughout the Santa Rita intrusive; the total ore in fissures is not great in contrast to the disseminated ore of the granodiorite porphyry. Clusters of small, blue-black pyritohedra are occasionally found as pseudomorphs after pyrite in the fissure fillings. Chalcocite veins and fissure fillings occur throughout the Santa Rita stock at all elevations within the two copper pits. They are found in the least altered porphyry and in the zone of leaching as well as in the highly altered granodiorite porphyry. The disseminated grains occur chiefly in the strongly altered porphyry. Veins, however, may be more abundant with depth in the highly silicified granodiorite porphyry. Vertical movements along the chalcocite veins are shown in many instances by prominent slickensides. Chalcocite veins cutting hematite and quartz veins are shown in Figure 22.

Native copper, of secondary origin, is found as tabular masses or sheets filling fractures in the altered granodiorite porphyry and in the overlying Beartooth and Colorado quartzites. Irregular sheets measuring a few inches in length and breadth and a fraction of an inch in thickness are common. Slabs of several hundred pounds have been found. Massive copper in large fissure fillings was mined from the metamorphosed sedimentary rocks by shallow underground operations before the opening of the pits. In cavities, the native copper modifies its usual sheet-like character and develops arborescent structures with incipient cubes and octahedra. Large, rounded arborescent masses rarely fill vugs. Native copper is found infrequently as disseminated grains in the altered granodiorite porphyry. Malachite is a common associate, invariably coating the copper. Cuprite cubes are occasionally found with the copper. Native copper replaces chalcocite in fissure fillings.

Cuprite, secondary in origin, occurs as well-formed cubes and cubes bevelled by dodecahedra. Translucent crystals measuring up to 2.0 cm. on a side show a deep blood-red to crimson color. Cuprite is found in the altered granodiorite porphyry as isolated grains, and is occasionally found as irregular grains in the matrix of the Whim Hill breccia or as larger clusters of crystals that had developed along a fracture surface. However, the best crystals are found as clusters in fissures and in cavities within the silicified granodiorite porphyry in a narrow zone of the northeast portion of the 5900 Bench. This zone has been followed down from higher levels. This occurrence of cuprite, characteristic of the oxidized zone, lies 350 feet below the rim of the South Pit. Cuprite is commonly asso-

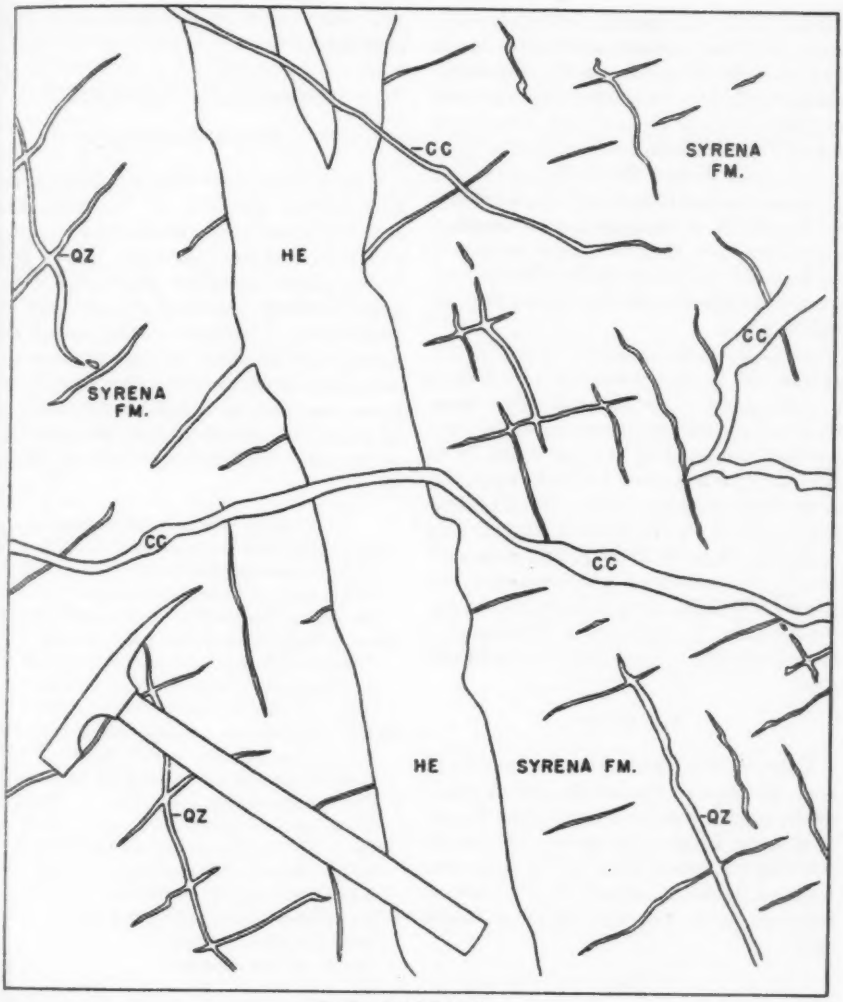


FIGURE 22.—CHALCOCITE VEINS CUTTING HEMATITE VEIN AND QUARTZ VEINS IN SYRENA FORMATION

ciated with sericite and late quartz. Native copper is an infrequent associate.

Within the oxidized zone of the upper benches of the South Pit, many secondary copper minerals are found in close association. Malachite occurs in banded form intercalated with azurite and melanconite. It is frequently found as fissure fillings in the capping. Malachite may show colloform banding in alternating dark-green and light-green layers; may occur with a dense botryoidal habit; or as slender needles in radiating aggregates measuring as much as

1.5 cm. in diameter. Azurite is generally structureless. It occurs rarely as irregular streaks and cavity fillings or as masses of tabular monoclinic crystals up to 1.0 cm. in diameter oriented at right angles to the wall rock bounding a fissure. Chrysocolla occurs in massive bands or as botryoidal clusters. The black earthy oxide of copper, believed to be melaconite, is found as streaks, bands, or crusts with other secondary copper minerals. Hydrous copper sulphate is common and continually forms efflorescent deposits and stains of a pale blue or green throughout the pits.

One of the most significant features in connection with the copper minerals is the absence of chalcopyrite in the main productive zones. Only one unconfirmed occurrence of this mineral has been reported from the South Pit to the east of the hematite zone on the north side. A fair amount of this mineral, however, has been found north of the North Pit in recent drilling operations. Here the diamond drill cores show chalcopyrite associated with magnetite and pyrite presumably as replacements of the carbonate rocks. It would seem to represent a typical contact metamorphic copper-bearing zone.

Molybdenum

Molybdenite is found as tiny, flattened grains both disseminated through the altered granodiorite porphyry and as deposits along fissures. It indicates a high-temperature mineralization following the consolidation of the Santa Rita intrusive. Minor amounts of molybdenum are recovered in the treatment of the chalcocite ores.

Zinc

Within the area of copper mining at Santa Rita, zinc minerals are conspicuously absent. Northwest of the North Pit, in the Kearney Mine which lies between the Hanover and Santa Rita intrusives and in an outcrop near the Sully School overlooking Santa Rita, sphalerite is found. However, zinc mineralization is apparently limited to replacement deposits in limestone associated with contact silicates which occur to the north, northwest, and perhaps northeast, rather than within the area of the Santa Rita intrusive itself. The extent of this mineralization is a problem for current exploration.[2]

Hydrothermal Alteration

Santa Rita Intrusive

General Discussion.—Detailed study of the hydrothermal alteration of the Santa Rita intrusive indicates a relationship between copper deposition and rock alteration. Several arbitrarily chosen alteration stages were distinguished through close field mapping with accompanying laboratory confirmation. The granodiorite porphyry of the intrusive was arbitrarily subdivided into four units found to be consistently mappable, numbered in order of progressive alteration from the essentially fresh to the completely destroyed rock (Table 3).

Summary—Stages of Alteration

Stage 1: Comparatively unaltered
- Feldspar cleavages lustrous
- Biotite black and lustrous
- No obvious clay patches

Stage 2: Incipient alteration
- Feldspars dull and cloudy
- Biotite frequently chloritized
- Occasional clay patches

Stage 3: Hydromica—argillic alteration
- Relict clay pseudomorphs of feldspars
- Brown hydromica replaces original biotite
- Ground mass argillic
- Minor quartz veinlets

Stage 4: Silicification and sericitization
- Relict feldspar outlines obliterated
- Relict biotite outlines destroyed
- Groundmass high in sericite and quartz
- Alunite veinlets common
- Quartz veinlets abundant

The progressive alteration of phenocrysts (Fig. 23) constitutues the most significant criteron applicable to field mapping. In the least-altered prophyry, hornblende phenocrysts may be found in limited numbers while biotite is abundant. In all but the most altered granodiorite porphyry, quartz phenocrysts in rounded grains are common and the outlines of plagioclase phenocrysts persist.

The most satisfactory phenocrysts for map-

[2] Since the above was written bodies of zinc ore have been encountered in drilling north of the *North Pit*.

ping are plagioclase and biotite. Plagioclase shows a change from lustrous euhedral feldspar through kaolinite and sericite pseudomorphs to tiny irregular clusters of alteration products. The feldspars are more plentiful and often persist as recognizable relics of the original granodiorite in more highly altered porphyry, but biotite is more quickly recognized in the field.

TABLE 3.—DISTRIBUTION OF MINERAL CONSTITUENTS OF THE SANTA RITA GRANODIORITE PORPHYRY

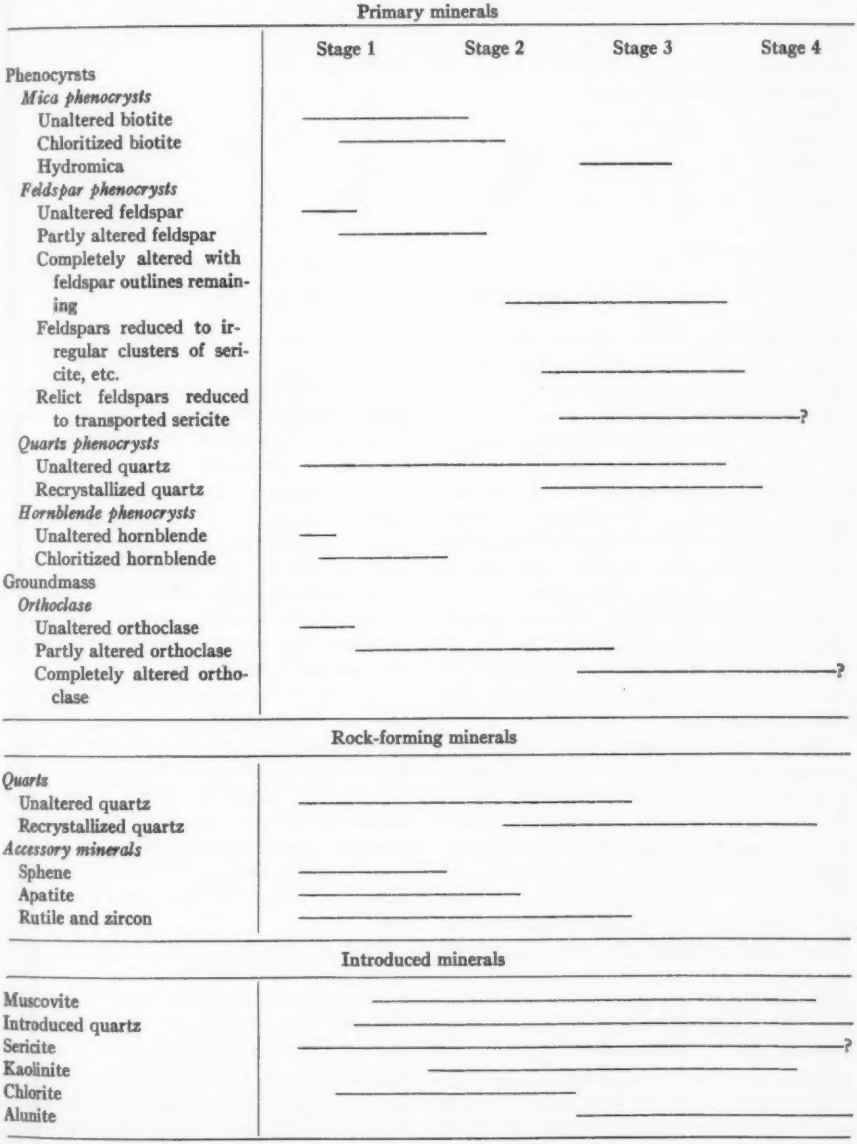
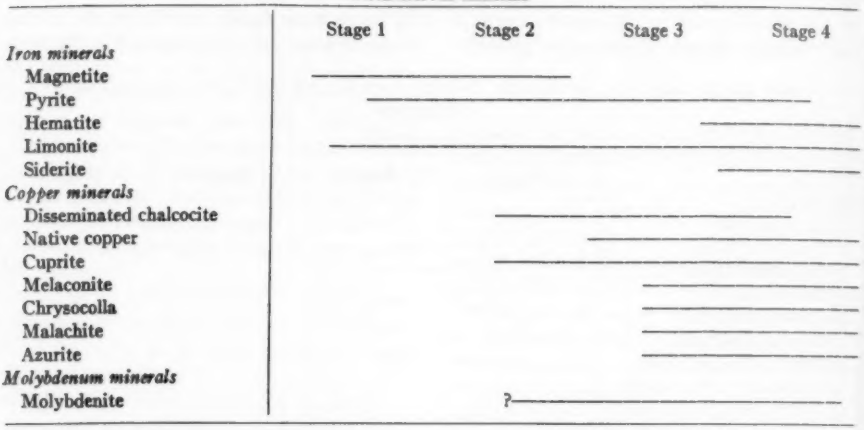


TABLE 3.—*Continued*

Metalliferous minerals



The bright black biotite crystals have been altered through a dull, gray-black stage to a waxy yellow-brown or buff pseudomorph. Like the feldspars, they have been destroyed in the most highly silicified granodiorite porphyry. Biotite is also abundant and persistent. Unlike the alteration aggregates of kaolinite and sericite after plagioclase, the alteration products after biotite are visible on routine field examination and differences in color and luster may be distinguished with reasonable facility.

Many thin sections have been used coupled with detailed field observations. The four alteration stages grade into each other, but in general contacts may be determined with reasonable accuracy.

The presence or absence of biotite and hydromica in Stages 1, 2 and 3 may be quickly determined, but the highly altered zones of Stages 3 and 4 are often interfingered. Here it may be tedious to determine whether hydromica is absent or merely sparsely distributed. Where even a few scattered hydromica grains have been observed the altered porphyry has been mapped as Stage 3. In the field, instances are found where Stage 2 passes abruptly into Stage 4 without an intermediate hydromica zone. Boundaries are often gradational, and it may be difficult to determine contacts more closely than to within a few feet.

The delineation of the four alteration stages has more definitely fixed the margins of the Santa Rita intrusive. Intrusive Stages 3 and 4 lie in contact with Syrena, Beartooth or Colorado sedimentary formations in a number of places. Stage 4 granodiorite porphyry, which lacks relict phenocrysts, contains considerable amounts of introduced quartz, and is often almost completely sericitized and is distinguished with difficulty at times from bleached, porous, metamorphosed Syrena sedimentary rocks or altered fine-grained quartz diorite of the middle and upper sills. Knowledge of the features of the alteration types in less altered portions of the intrusive has aided in making the necessary distinctions.

The detailed mapping of the Santa Rita stock on the basis of the four stages has revealed an unsuspected trend in the broad alteration pattern. An axis (Fig. 16) or belt which indicates the elongation of the least altered core of the intrusive was found to pass southeastward from the North Pit through the Central Island into the South Pit and thence under dump and landslide debris toward the southeast.

The axis represents a core of relatively unaltered granodiorite porphyry. The core seems to be the residual central portion of the primary intrusive, largely untouched by later hydrothermal solutions that operated marginally. The significance of the structure is emphasized by the parallelism of linear aplitic zones, quartz porphyry dikes, apophyses of granodiorite por-

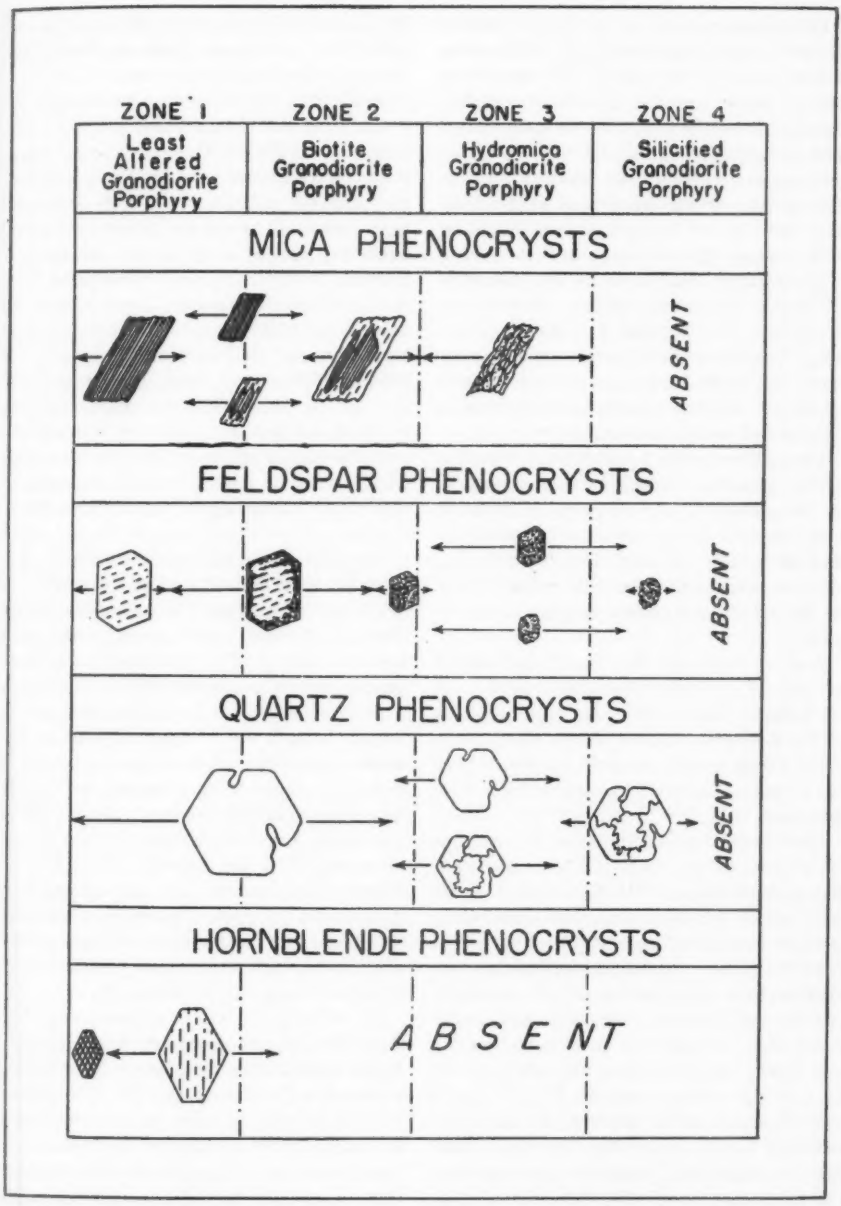


FIGURE 23.—ALTERATION OF PHENOCRYSTS IN THE SANTA RITA GRANODIORITE PORPHYRY

phyry in the bordering sedimentary series and finally by the similar trends shown by the uparched sediments on the flanks of the stock. The axis corresponds more or less to the crest of the overlying arch produced by the invasion of the stock but subsequently eroded.

The groundmass of the porphyry remained relatively untouched during the early stages of the hydrothermal phase, but phenocrysts already partly corroded before the complete consolidation of the intrusive were more susceptible to hydrothermal alteration. Hornblende phenocrysts were chloritized. Biotite was chloritized or reduced to hydromica. Plagioclase feldspar was altered to sericite and kaolinite. With intense hydrothermal activity over a longer period of time, the biotite and orthoclase of the groundmass were altered to chlorite and sericite with the injection of abundant quartz. Where hydrothermal alteration was most intense the original phenocrysts were largely obliterated, and the groundmass reduced to an aggregate of sericite and secondary quartz.

The most extensive hydrothermal alteration of the granodiorite porphyry was observed in the western and southern portions of the Santa Rita intrusive and in cores from beneath the East Hills. The distribution of hydrothermal solutions in outer portions of the intrusive may be due to more abundant fissures and fractures.

Areas of alteration.—The Santa Rita intrusive and related formations have been mapped on the Stripping Plat of the Chino Mines Division of the Kennecott Copper Corporation, (July, 1946), a map revised quarterly on a scale of 100 feet to the inch. Plate 1 has been reduced from this scale.

Benches are numbered to show the elevation in feet above sea level; for example: 6026 Bench, 5984 Bench, 5900 Bench. Other reference points include railroad switches, assay stations established along railroad tracks at scenes of present operations, inclines between benches, fixed triangulation stations, and many near-by local features. From these many reference points, features may be located by pacing and taping distances along railroad tracks or by utilizing compass bearings. The compass is often unreliable within the South Pit due to the overhead cables, power lines on the benches, railroad tracks, and electrically operated shovels, locomotives, and drills. Constant stripping of the ore and waste from the benches of the south and southeast walls to the South Pit causes inescapable, though probably not significant, inaccuracies in location. The North Pit, abandoned since 1927, does not present difficulties of this sort, but weathering has obscured many of the exposures.

South Pit.—Exposures along the banks between successive benches are excellent. The banks, 40 to 70 feet high, provide an opportunity for clear observation of the variation of the alteration stages with depth. Traverses have been made at the foot and edge of every bank. The geology of the inaccessible portions between the top and base are interpolated. Most of the rock has been studied in place above the talus. Some broken rock is debris displaced by bull-dozers and blasting from higher banks and benches. Where the talus cone covers the face of the bank, field examination usually indicates the most frequent rock type and the probable nature of the underlying formations. The problem of evaluating bank exposures is difficult only where operations are immediately current.

Mapping of the flat bench surfaces is considerably more difficult and much less reliable. While rock formations are well-exposed in the steep, 40–70 foot banks, these occupy little horizontal space. The rock formations of the benches, which average 50–125 feet and attain a maximum of 350 feet in breadth, are generally buried beneath 4–12 inches of crushed and boken rock. Only infrequently small areas of bed rock appear from beneath the rubble. The same situation prevails at the bottom of the South Pit. The lowermost 5900 Bench, measuring 2500 feet long by 850 feet at its widest point, shows only rare outcrops of granodiorite porphyry generally hidden by rock fragments which may have been carried a considerable distance by blasting, shovel operations, ore trains, or by bull-dozers.

In mapping and collecting specimens of altered granodiorite porphyry from the 5900 Bench and all higher benches on the south and southeast walls of the South Pit, it was necessary to dig shallow holes, usually less than 1 foot deep to the underlying bed rock. These holes were dug at regular intervals of 50 feet along many intersecting traverses on the pit bottom and likewise in parallel or converging, closely-spaced traverses on the higher benches. Churn-drill holes, for blasting, located along the margins of benches or in the bottom of the

South Pit, yield information on the nature of the underlying granodiorite porphyry.

Along the north and west walls of the South Pit, permanent railroad tracks follow benches covered with several feet of fill and ballast. Exposures are infrequent and limited to ballast-free ditches. On rubble-covered benches, small rises occasionally scraped clean by the bulldozers indicate bed rock near the surface.

North Pit.—Mapping of the North Pit has been less detailed than the South Pit. Several portions of benches were inaccessible as a result of slumping during years of idleness. Many banks were also hidden by weathered talus slopes. Mr. Gerald J. Ballmer has studied much of the north wall (1943), and his observations were of great assistance in the completion of the alteration map. More recently Mr. George Ordonez has studied the region north of the North Pit and has established the geology of the margin in greater detail.

Central Island and pit margins.—Exposures are relatively scarce on the Central Island between the pits. Buildings, cultivation, and a large waste dump on the western end obscure most of the outcrops. The best exposures are found in the vicinity of the water tank on the small hill north of the village.

In some places areas above the pit rims are built over, or buried by waste dumps. Southeast of the South Pit there is much landslide debris derived from the Tertiary (Miocene?) lava and tuff formations capping the hills immediately to the southeast. Exposures of the Colorado formation and related upper and middle quartz diorite porphyry sills are abundant on the hills south and east of the South Pit rim. Alteration in these units has been observed but has not been studied in detail comparable to the study in the South Pit.

Contacts.—Contacts are shown as dotted lines since abrupt changes in rock units are rare. Minor errors in carrying contacts across talus banks and benches may be expected.

The irregular contact between the intrusive stock and the intruded Cretaceous sills and sedimentary rocks on the south and southwest walls of the South Pit is partly obscured by debris and weathering. Relict phenocrysts furnish the chief criterion by which the altered porphyry may be distinguished from the finer-textured but likewise highly altered sills and sedimentary rocks. Contacts between the altered granodiorite porphyry and the bleached Syrena formation are largely obscured but iron oxides along the contact zone are regarded as marginal facies of the metamorphosed sedimentary rocks.

Alteration Stage One.—The least altered core of the Santa Rita stock (Pl. 1) is confined to the North Pit. The trend of this core of fresh rock points to the trend of the emplacement of the Santa Rita intrusive. The belt as observed is about 1400 feet long striking N33 W., in general parallel to the strike of several aplitic zones, the hydromica granodiorite porphyry apophyses, and quartz porphyry dikes. The marginal contacts between the sedimentary rocks and the intrusive are also roughly parallel. This core of fresh porphyry may be considered the unaltered center of the intrusive, and it may be the axis of structural uplift as well.

It may be traced from the north rim of the Pit down the benches to the reservoir at the bottom and reappears on the south wall extending upwards almost to the rim. A subsidiary triangular body of fresh granodiorite porphyry with a north-striking axis extends for 450 feet parallel to the axis of the breccia. This is the westernmost occurrence of the least-altered granodiorite porphyry on the north wall of the North Pit. The best outcrops of Stage 1 are found along this north wall. The maximum width of the least-altered porphyry zone is 1000 feet at this point tapering toward the southeast to 250 feet on the south wall.

The least-altered granodiorite porphyry occurs in well-defined exposures presenting sharp rectangular fracture surfaces. Outcrops in zones of advanced alteration have lost the rectilinear appearance of Stage 1 porphyry and are replaced by intricate, intersecting networks of mineralized or siliceous veins and fissure fillings.

The biotite of Stage 1 (Fig. 24) is relatively fresh. In highly mineralized phases adjoining fissures, the biotite may be partially replaced by pyrite. The iron-rich biotite was probably leached by hydrothermal solutions. The typical black-brown to buff pleochroism has been changed to the green to pale-green pleochroism of chlorite. The iron freed during the leaching

process remained as secondary magnetite in the cleavage planes of the mica. Later sulphide solutions changed it to pyrite. The more pyrite found in the mica, the paler the absorption

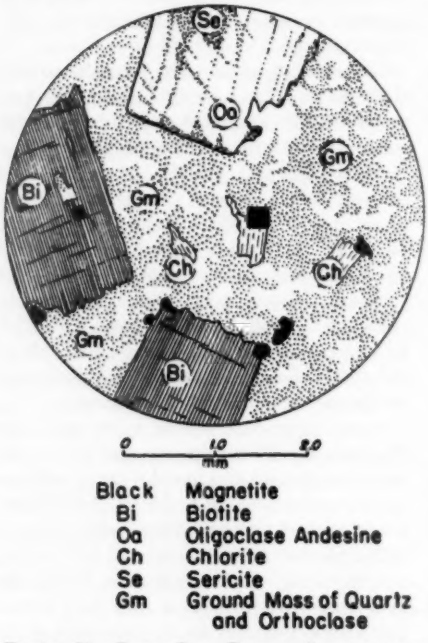


FIGURE 24.—STAGE ONE—BIOTITE GRANODIORITE PORPHYRY

colors become. It is likely that much pyritic replacement of biotite supplemented this process, as some micas are literally riddled with the sulphide.

The euhedral plagioclase crystals show sericite development along cleavage and fracture planes, but complete alteration characteristic of advanced alteration stages is absent. Limonitic aggregates are found in altered portions of the phenocrysts.

Hornblende was the first of the phenocryst minerals to be destroyed in the alteration process at Santa Rita. It shows varying stages of alteration to chlorite in the freshest rock. Pseudomorphic clusters of biotite and magnetite after hornblende are also found. Other instances of the biotitization of hornblende by hydrothermal solutions have been described at Marysville, Montana (Barrell, 1907, p. 140) and in the Eagle River district, Alaska (Knopf, 1912, p. 37). The typical amphibole outline is still preserved in these instances of replacement. Occasionally fresh andesine laths occur in such aggregates, suggesting reaction between the early-formed hornblende and the still fluid portions of the magma. Quartz and orthoclase corresponding to the texture of the groundmass have also crystallized within the margins of the corroded amphiboles. The biotite of such a pseudomorphic aggregate is a black-brown to pale olive green similar to that formed during primary crystallization. Interstitial chlorite is derived from the alteration of hornblende and biotite. The feldspar of the groundmass is more resistant to alteration than the phenocrysts. Limonite specks, .01–.03 mm. in diameter, occur marginal to pyrite. Scattered quartz veins cut all elements of the rock.

Magnetite is associated with the biotite, hornblende, and chlorite. When pyrite is present, the magnetite is generally absent. The two minerals seem to be somewhat exclusive. When found together, the pyrite may enclose grains of the magnetite suggesting replacement by sulphur-bearing solutions. Pyrite also cuts across tiny magnetite veinlets. The pyrite veinlets in turn are cut by late quartz. Cuprite found in places in the North Pit is presumably secondary.

Alteration stage two.—The alteration of Stage 2 (Pl. 1) increases away from the least-altered central core. Exposures are nearly equal in area to those of the hydromica granodiorite prophyry. Stage 2 is most extensively exposed in the North Pit, beneath most of the Central Island of Santa Rita and in irregular zones comprising a large part of the north wall of the South Pit. This continuous mass of about 3,000,000 square feet encompasses the core of least-altered granodiorite porphyry of Stage 1; the bodies of Whim Hill breccia; the linear aplitic zones and minor amounts of Stage 3 and Stage 4 porphyry.

Stage 2 is found along the east side of the intrusive for almost a mile. The trend varies from N40°W in the north wall of the North Pit to roughly due north in the northeast wall of the South Pit. To the west, this main body of biotite granodiorite porphyry includes and

penetrates pendants of the Syrena and Beartooth formations along the benches of the west wall of the North Pit.

The second largest exposed area of Stage 2 occurs in three irregular masses bordered by Stage 3 on the east wall of the South Pit.

The full bed-rock extent of this area is not known since its exposures are partly hidden under waste and landslide or talus.

Biotite granodiorite porphyry of Stage 2 is exposed throughout the Garman Adit 1200 feet east of the South Pit. Diamond drill holes 922 and 925 southwest of Niagara Gulch also penetrated areas of biotite granodiorite porphyry close to the surface. Much of the buried porphyry to the east-southeast of the South Pit appears to be Stage 2, but the boundaries can only be inferred because of inadequate surface exposures.

General dike-like bodies of biotite granodiorite porphyry occur in the east third of the South Pit. These may be traced from bench to bench and trend N10°E to N35°W. They range from 10 to 35 feet wide and vary from 150 to 180 feet long. They are somewhat obscured by debris.

The explanation of these tabular masses is not entirely clear. Phases of the "dikes" have suffered alteration locally to hydromica granodiorite porphyry. Alteration does not explain the irregular, linear character. They may represent tensional fractures opened parallel to the northerly axis of the stock to receive a late surge of the granodiorite porphyry magma. Hydrothermal alteration had already made some progress prior to this possible resurgence of fluid material. In the absence of more definite petrographic evidence, two separate intrusions of the Santa Rita stock are considered unlikely.

In most exposures, Stage 2 shows prominent phenocrysts of biotite, feldspar, and occasionally hornblende and quartz in a fine-grained, gray-green groundmass. With increased alteration, the biotite cleavage surfaces decrease in area, lose their vitreous luster and may become marginally bleached. The lustrous plagioclase phenocrysts of Stage 1 assume a dull, greenish-white, earthy appearance. Former hornblende crystals when found are dark gray with a characteristically dull luster. The outcrops, rounded and iron-stained, no longer exhibit the sharp, rectangular blocks typical of Stage 1 porphyry.

An uncommon silicified phase represents a higher degree of alteration of Stage 2. With the introduction of silica, the granular surface of fracturing becomes even and regular like the surface of a quartzite. Still the characteristic outlines and colors of the phenocrysts of biotite and plagioclase remain. With increased silicification, the original phenocrysts become sparse until ultimately only quartz, flakes of biotite, and rare feldspar outlines remain.

The biotite granodiorite porphyry (Stage 2) may be displaced by a hornblende-bearing granodiorite prophyry. Hornblende-rich rock occurs along the 6100 and 6165 Benches of the east and southeast walls of the South Pit, indicating original hornblende-rich phases as well as biotite-bearing portions of the Santa Rita intrusive.

This phase of the intrusive was first mapped as hornblende granodiorite porphyry but microscopic examination shows that the original hornblende has been replaced by biotite and chlorite. The hornblende-bearing rock is of the same relative degree of alteration as the Stage 2 granodiorite porphyry with which it interfingers.

Pegmatitic as well as normal phases of the biotite granodiorite porphyry occur as fragments in the Whim Hill breccia exposed on the northern edge of the Central Island. Other pegmatitic varieties occur infrequently in small veins on the north wall of the South Pit in the biotite granodiorite porphyry zone. The biotite granodiorite pegmatite shows clustered and intergrown flakes of biotite 1.0–2.0 cm. in diameter associated with pink orthoclase crystals 2.0–4.0 cm. in length. The quartz of the pegmatite may occur intergrown with orthoclase, as massive veins, or as prismatic crystals measuring up to 1.0 cm. in diameter. Some coarse-grained phases show only biotite and quartz.

A mixed biotite porphyry rock occurs with the aplite sheets in the aplitic zones of the North Pit. Another mixed rock is found in the eastern end of the north wall of the South Pit. Here along the extremely irregular contact between the igneous mass and the metamor-

phosed Syrena formation, the biotite granodiorite porphyryhas saturated the sedimentary rocks. The fine-grained, iron-bearing, schistose sedimentary rocks are permeated with biotite and feldspar lenses, veins, and replacements. Where the introduced igneous material predominated, the rock was mapped as Stage 2 granodiorite porphyry.

Biotite phenocrysts in Stage 2 have a ragged, shredded appearance. As alteration proceeds, the biotite exchanges its characteristically deep absorption for a pale olive-brown or reddish-brown to colorless pleochroism.

Chlorite, the principal secondary product derived from biotite in Stage 2, first appears along fractures and cleavage traces at the margins of the biotite grains (Fig. 25). It then penetrates along the cleavage planes opened by deformation while at the same time it forms a margin of replacement about the entire grain of biotite. The pale yellow-green to deep yellow-green or blue-green pleochroism of the chlorite stands in marked contrast to the absorption of the biotite. The chlorite frequently contains specks of limonite which in this early stage of alteration may have been derived in place from the biotite. As alteration to chlorite proceeds the entire grain of biotite may eventually become chloritized, or a residual, unaltered core may still remain. The biotite grain seems to be first crushed and fragmented, then leached of its iron content, and finally altered to chlorite.

The chlorite derived from the hornblende and biotite, so prominent in Stages 1 and 2, disappears in the more intensely altered granodiorite porphyry of Stages 3 and 4. Chlorite appears to represent an intermediate stage of alteration. It seems that the chlorite itself is replaced by sericite as alteration proceeds. Weed (1912, p. 89) and Kirk (1912, p. 61) observe chlorite passing into sericite in the altered Butte quartz monzonite. Emmons and Calkins (1913, p. 175) noticed that chlorite occurred in the early stages at Philipsburg, Montana, but was absent where alteration was intense.

Alteration may proceed along other lines. Sericite, muscovite, hydromica, and quartz may develop along the cleavage planes and gradually extend through the greater portion of a biotite grain. In advanced stages of alteration, hydromica phenocrysts typical of Stage 3 begin to appear having measurements of 1.0–1.7 mm., but as long as recognizable biotite may be observed, the granodiorite porphyry is classified as Stage 2.

Feldspar phenocrysts are not entirely altered in much of the granodiorite porphyry of Stage 2. Prominent albite twinning and occasional pericline twinning appear in these slightly altered feldspars. However, the freshest plagioclase phenocrysts are partially sericitized and kaolinized along the cleavage and fracture surfaces. With higher alteration, the feldspars become highly fractured with partial alteration to sericite and kaolinite. In advanced stages of feldspar alteration in Stage 2, the feldspar outlines alone are preserved as the sericitization and kaolinization are completed.

The large pink feldspars found with the pegmatitic phases are sericitized orthoclase crystals. In the pegmatite two generations of feldspars having phenocryst dimensions frequently occur. Smaller phenocrysts, measuring 1.0–1.4 mm. long and now completely altered to sericite and kaolinite, were probably oligoclase-andesine of early crystallization. Later, larger orthoclase crystals are relatively fresh, untwinned, partially sericitized, and usually measure 2.0–2.8 mm. long although 4.0 cm. crystals have been found.

Hornblende phenocrysts where found in the granodiorite porphyry of Stage 2 along the 6100 and 6165 Benches of the east wall of the South Pit appear to be well-preserved. Under the microscope, however, they are seen to be completely reduced to skeletal grains by the late corrosive action of the crystallizing groundmass of quartz and orthoclase. The best preserved specimens show amphibole outlines and prismatic cleavage. All the hornblende interstitial to the invading fine-grained groundmass has been completely altered to chlorite in most instances and less frequently to biotite. Weed (1912, p. 87) noted the chloritization of the hornblende and biotite of the Butte quartz monzonite. Such a transformation is characteristic of the progressive alteration from Stage 1 to Stage 2 in the Santa Rita granodiorite porphyry. The chlorite of alteration generally shows green to pale-green pleochroism with maximum absorption in the vibration plane

of the lower nicol. All grains show parallel extinction. These relict grains of hornblende, almost completely chloritized, measure .7–1.5 mm. thick.

Areas of altered hornblende crystals may contain many irregular grains and cubes of magnetite and pyrite measuring .03–.5 mm. in diameter. The magnetite would seem to have been derived from the hornblende. The pyrite may have been formed by the action of sulphur-bearing solutions on the indigenous magnetite.

The quartz remains unaltered, but the orthoclase is always partly replaced and altered. The orthoclase becomes charged with sericite as alteration increases. In highly altered forms of Stage 2, sericite becomes a major constituent. Muscovite, chlorite, pyrite, magnetite, and uncommon oligoclase or clay minerals are found in minor amounts. Frequently a distinct separation of quartz grains and sericite scales indicates segregation accompanying alteration.

Graphic and granophyric intergrowths between the orthoclase and quartz comprise the groundmasses of Stage 2 porphyry in contact with aplites of the North Pit.

Biotite veins frequently cut the groundmass of the biotite granodiorite porphyry. It is believed that they are of late hydrothermal deposition formed by the solution and redeposition of biotite of the groundmass and not like the typical primary biotite of the porphyry. This biotite shows a paler pleochroism of light olive-brown to colorless indicating a loss of iron content between the time solutions dissolved the biotite material from the primary micas and the time it was redeposited in the cavities and fissures. If the late micas were formed by crystallization from ascending solutions, these solutions were apparently iron-poor.

The fine-grained groundmass biotites are generally fresh, while the earlier biotite phenocrysts observed in hand specimens usually show considerable shredding and chloritization. In advanced Stage 2 even the fine-grained biotite of the groundmass is altered to chlorite. In clusters of biotite laths, chlorite invariably occupies the interstices (Fig. 25). In some of these biotite segregations, the ever-present chlorite forms most of the aggregate. Limonite and subhedral magnetite are found with the chlorite indicating derivation from the biotite flakes.

Although considerably less sericite occurs in Stage 2 than in Stages 3 and 4, it becomes one

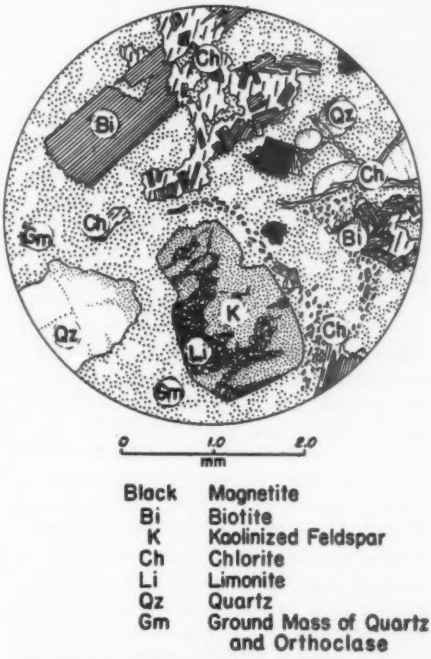


FIGURE 25.—STAGE TWO—ALTERED BIOTITE GRANODIORITE PORPHYRY

of the major constituents in advanced phases of Stage 2. As Stage 3 is approached, sericite becomes abundant, formed at the expense of the phenocrysts and groundmass crystals of feldspar and biotite. Most aggregates of sericite are regarded as derived from the alteration of the feldspar phenocrysts. The sericite may be included in the quartz and feldspar grains of the groundmass or may occur interstitial to them.

Secondary constituents of the groundmass that occur in minor amounts are muscovite, limonite, and vein quartz. The muscovite occurs as residual flakes of bleached biotite. Schwartz (1939, p. 192) noted: "Not all muscovite which forms during hydrothermal alteration is the fibrous sericite variety. Biotite, for example, frequently bleaches or alters to muscovite,

presumably by removal of iron." Vein quartz is noticeable in Stage 2 although not as prominent as in 3 and 4. The veins range in width from fractions of a millimeter to several inches. The interlocking quartz grains vary from .03 to 2.0 mm. thick. These quartz veins generally cut all elements of the biotite granodiorite porphyry except the latest pyrite. The quartz veins may follow and embay the pyrite where they do not actually cut through it. Pyrite may occur in quartz veins both as early vein margins and as later central fillings. Some late quartz veins show central deposits of limonite-strained mixtures of kaolinite and alunite. These clay-quartz veins cut across the earlier biotite veins.

Alteration stage three.—Stage 3 is the principal ore-bearing rock of Santa Rita. As a unit it yields the highest assay values and where exposed the most intensive mining operations are conducted. It occurs on either side of the central axis of lesser alteration (Pl. 1).

Stage 2 lies to the north and east and Stage 4 to the west, although the exposures are often interpenetrating. On the east wall, stage 3 encloses a relatively fresh area of Stage 2 biotite granodiorite porphyry. It might be assumed that the upper mass of hydromica-bearing rock is a supergene alteration phase of the underlying biotite granodiorite porphyry, but the presence of large masses of relatively fresh granodiorite porphyry at the surface elsewhere fails to confirm this opinion.

Apophyses of hydromica granodiorite porphyry intrude the altered Cretaceous sills and sedimentary rocks on both the east and southwest walls of the South Pit. On the east the Colorado shale and quartzite are largely replaced for 1100 feet by hydromica granodiorite porphyry that was injected along the lower contact of the formation with the underlying Beartooth quartzite. The lower contacts are hidden by talus, but the fingers of porphyry that have pierced the roof-forming, sedimentary rocks of the Colorado formation and associated middle and upper quartz diorite porphyry sills may be traced on the surface and in drill holes. Through the hills east of the South Pit, some of these fingers may be followed for 1000 feet east and northeast. Their width averages from 25 to 40 feet, but may be as great as 100 feet where the roof of the stock has been partly removed by erosion. Southwest of the South Pit, apophyses of hydromica-bearing granodiorite porphyry may be traced for distances of nearly 1300 feet through the Colorado sedimentary rocks and associated sills. They generally strike westerly but occasionally a southwest trend is found. These stringers range up to 50 feet wide.

Stage 3 also occurs in the North Pit as dike-like masses cutting the sedimentary rocks and marginal stock rock east of the central axis of the Santa Rita intrusive. North-trending apophyses have varying strikes ranging from N20°E to N30°W. They are roughly parallel to one another, to the aplitic zones, to the contact of the stock and the sedimentary rocks, and to the principal axis of the intrusive. The terminations of these linear bodies are not known but they seem to have a minimum length of 300–1500 feet. They either end north of the pit rim or are obscured by the water in the pit bottom. These dikes of hydromica granodiorite porphyry are 50–60 feet wide on the southeast wall of the North Pit.

The hydromica-bearing stage is a light-gray rock traversed by numerous quartz, pyrite, kaolinite, and alunite veins up to 2–3 inches wide. Where least altered, it shows prominent phenocrysts of gray-brown, bronze, buff, straw or honey-colored hydromica pseudomorphs after biotite; chalky, euhedral feldspar laths replaced by clay or sericite; and occasional rounded quartz phenocrysts. Peterson, Gilbert and Quick (1946, p. 828) described similar selective alteration of the phenocrysts in the quartz monzonite of the Castle Dome deposit, Arizona. The plagioclase of the intermediate zone "has a chalky appearance and rarely shows any twinning striations. Some of the biotite is altered to a soft, buff-colored micaceous mineral either in the form of pseudomorphs or aggregates." In field mapping, the most convenient single criterion is the hydromica pseudomorph after biotite. As degree of alteration increases, the hydromicas become sparse, the feldspars gradually disappear, and the original quartz phenocrysts become obscured by introduced quartz and vein quartz. In advanced Stage 3, hydromicas are scarce and almost completely destroyed. The boundaries of the hydromica zone have been extended to include

these areas where hydromica can be found although in many cases considerable search is required.

The hydromica pseudomorphs after biotite, when viewed in thin sections, are pale-yellow to colorless aggregates generally preserving the mica structure. They appear as finely divided scraps, relict mica pseudomorphs, or as euhedral grains showing excellently preserving outlines (Fig. 26). Including all recognizable fragments, the altered biotite groups measure .1–5.2 mm. Most typical grains range from .5–1.7 mm. Interference colors are first order gray and white and the hydromicas appear in part as shredded, fibrous aggregates under crossed nicols. The fibers are oriented parallel to the basal cleavage of the original biotite. These fibers resemble sericite but do not have the characteristic high-order interference colors. In rare instances radial aggregates of hydromica not occurring as pseudomorphs are found in association with sericite. These have diameters up to .08 mm.

Refractive indices of black biotite, partly altered biotite, and the pale-brown pseudomorphous clay mineral from the South Pit were determined as follows:

	$n\alpha$	$n\beta$	$n\gamma$
Black biotite	1.568	1.634	1.635
Partly altered	1.554	1.602	1.604
Pale-brown pseudomorph	1.545	1.559	1.560

Na-light (20° C) ± .002

Grim (1934) reports $n\alpha$—1.544 and $n\gamma$—1.574 for illite from Grundy County, Illinois.

The hydromica grains are aggregates of several minerals, typically biotite, limonite, a white opaque material, sericite, kaolinite and quartz in addition to a clay mineral of the "illite"[3] type.

Differential thermal analysis of two specimens of hand-picked hydromica aggregates indicates 30 ± 10% illite-type clay mineral, 25 ± 10% kaolinite, 20 ± 5% quartz plus some relatively inert material such as sericite (Kerr and Kulp, 1948).

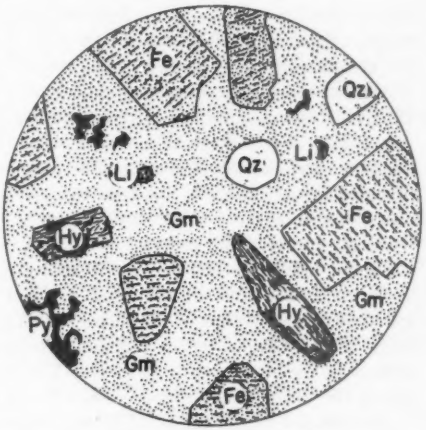


FIGURE 26.—STAGE THREE—HYDROMICA GRANODIORITE PORPHYRY

The biotite occasionally occurs as cores surrounded by hydromica. The unaltered cores of residual biotite show absorption from black-brown to gray or tan. This is the usual pleochroism found in the unaltered biotites of Stages 1 and 2. The limonite imparts the brown, buff, straw, or honey color to the hydromicas of Stage 3 as seen in the hand specimen. The limonite may be transported, having been derived from the pyrite of the granodiorite porphyry, or it may be indigenous, having been formed from the alteration of the original biotite. Infrequently the hydromica grains are replaced by pyrite with marginal chalcocite.

[3] This term is believed to be the equivalent of the "hydrous mica" or "hydromica" of Ross and Hendricks (1945). As used it is a field term for the brown pseudomorphs after biotite.

Such possible synonyms as illite, hydromica, bravaisite, glimmerton, and hydrobiotite have been reviewed since this article was written (Kerr and Hamilton, Preliminary Report No. 1, Glossary of Clay Mineral Names, Amer. Pet. Inst. Project 49, distributed by the Director of the Institute, Dallas, Texas).

The sulphides were introduced along the cleavage planes of the original biotite.

Outlines of completely altered feldspar phenocrysts may be abundant, rare, or absent in Stage 3 porphyry. Unaltered feldspars are not found. Even remnant cores of feldspars are rare in the freshest hydromica granodriorite porphyry. Outlines of euhedral feldspar crystals are common although in most instances the crystals have been completely sericitized (Fig. 26) yet showing ghost plagioclase twinning. The highly altered feldspar contains sericite, kaolinite, and secondary quartz. The altered feldspars range from .4 to 7.5 mm. with most altered phenocrysts .5 to 3.2 mm. They may be deeply embayed and corroded by patches of relatively unaltered, interlocking quartz and orthoclase of the ground mass. When the feldspar has been converted to kaolinite, the outlines of the original crystals remain better defined as the alteration proceeds than if sericite is the main product. Occasionally the altered feldspars show patches of fibrous hydromica with the kaolinite and sericite.

An unusual example of a large zonal feldspar phenocryst measuring 4.8 mm. was found with two included hydromica crystals .9–1.0 mm. in diameter. The original biotite was apparently earlier than the feldspar in the original sequence of crystallization. In the alteration process, the outer feldspar had been changed to kaolinite while the hydromica formed at the expense of the biotite.

Due to absorbed copper stain, euhedral feldspars of the hydromica granodiorite porphyry sometimes appear green when studied in hand specimens. The staining frequently reproduces the zonal banding of the original feldspar. Generally, the feldspar outlines disappear before the outlines of the hydromica are destroyed.

Quartz is an uncommon phenocryst and may be entirely absent, but when present it forms the most stable phenocrysts and may be found as recrystallized grains after the complete destruction of the persistent hydromica. The quartz phenocrysts in Stage 3, when observed, are usually clear, well-rounded, partly-corroded, embayed grains. Stress with recrystallization is frequently shown by wavy extinction. The quartz phenocrysts range in diameter from .5 to 6.5 mm. with the average phenocrysts measuring .5–3.0 mm. Occasionally the larger quartz phenocrysts show a thin marginal halo of sericite alteration .08–.1 mm. wide. The long axes of the grains of sericite are oriented normal to the quartz boundaries. Minute fluid cavities occur oriented in crystallographic directions. Where the quartz is embayed, it is adjacent to the groundmass of quartz and sericitized and kaolinized orthoclase. The corrosion and the rounding of the quartz grains probably occurred during the late magmatic period.

Early in Stage 3, the groundmass may show primary quartz, orthoclase, and occasional biotite. These constituents are absent in the advanced alteration phases of Stage 3. The primary quartz has been recrystallized, the orthoclase and biotite completely destroyed. The secondary constituents of the groundmass are quartz, sericite, kaolinite, hydromica, and limonite.

The orthoclase of the groundmass appears relatively fresh long after the feldspar phenocrysts have been reduced to sericitic aggregates, and sericitized orthoclase in the groundmass can still be identified after the relicts of the feldspar phenocrysts are gone. Knopf (1913, p. 56) noticed selective sericitization of the feldspars in the quartz monzonite wall rock of vein deposits at Marysville, Montana. The orthoclase occurs practically exempt from alteration. Peterson, Gilbert, and Quick (1946, p. 831) noticed this same persistence of primary orthoclase with original quartz in the highly altered quartz monzonite porphyry of the Castle Dome area, Arizona. The orthoclase remains after the oligoclase and biotite have been reduced to pseudomorphous aggregates. Describing the Santa Rita granodiorite porphyry, Landon (1929) observed, "Sericitization has affected the feldspar phenocrysts more than the feldspars of the groundmass." The large feldspar phenocrysts in the freshest rock of the hydromica granodiorite porphyry will show 70–100 per cent alteration to sericite; the associated groundmass feldspars may show but 5 to 20 per cent alteration. Rarely, tiny biotite grains less than .4 mm. occur in the primary quartz and orthoclase of the groundmass. They show absorption from pale brown to deep olive-brown. The biotite of the groundmass is only found in the least-altered hydromica grano-

diorite porphyry. Again the groundmass demonstrates less alteration than the phenocrysts since the large biotite crystals typical of Stages 1 and 2 have been already converted to hydromica. Rare magnetite and zircon grains .2–.4 mm. are found in the freshest porphyry of Stage 3.

Among the secondary constituents of the groundmass, introduced quartz and sericite are the most important. Secondary quartz occurs as fine-grained, rounded, anhedral crystals. These replace orthoclase and primary quartz from which they are distinguished by a lack of interlocking boundaries. Introduced quartz also appears in abundant, intersecting veins that cut both the groundmass and the phenocrysts. In more intense alteration, the amount of secondary quartz and quartz veinlets increases. Recognizable quartz veinlets range from .02 mm. to 5.0–7.5 cm. wide.

The earlier, interlocking quartz grains are generally larger than the introduced quartz and vary from .02 to 1.0 mm. thick. Occasionally a quartz vein shows a double row of interlocking grains indicating simultaneous growth from either side of the fissure. The vein quartz is extremely fresh and free from all inclusions. Even in the limonite-stained capping, the vein quartz remains clear.

Most of the sericite found in the groundmass occurs interstitially among quartz grains. This ubiquitous mineral is also found as fine-grained aggregates and veinlets cutting both the groundmass and the phenocrysts. The sericite is matted, fibrous, and scaly generally measuring .003–.06 mm. thick. Though some sericite has been developed from the orthoclase of the groundmass, most has been derived from the alteration of the feldspar phenocrysts. Eventually all sericite becomes transported as the relict aggregates of feldspar outlines are broken up and the sericite dispersed.

Alteration stage four.—In its most advanced alteration, the Santa Rita intrusive becomes the silicified granodiorite porphyry of Stage 4. Stage 4 is exposed in the South Pit west of the exposures of Stage 3 (Pl. 1). The greatest concentration is in the lowermost benches and on the bottom 5900 Bench of the South Pit (Pl. 8). The occurrence of so much of Stage 4 350 feet below the rim of the pit in these lowermost exposures indicates the hydrothermal character of the alteration.

At the west end of the Central Island, the silicified stage occurs in irregular blocks which extend into both pits on either side of U. S. Highway 180. In the North Pit, it occurs in larger masses, while in the South Pit, it forms irregular marginal fingers intruding the Colorado and Beartooth quartzites. Here the Stage 4 granodiorite porphyry has a marginal occurrence at the contact between the intrusive and the adjoining sedimentary rocks.

A third body occurs as a spindle-shaped linear mass along the southeast wall of the North Pit. This area simulates somewhat the parallel aplite fingers on the northeast benches of the North Pit. On the opposite wall of the North Pit there are four masses of Stage 4 granodiorite prophyry which intrude the metamerphosed sedimentary rocks or lie along their contacts with the Santa Rita intrusive.

The silicified granodiorite porphyry is a light-gray to buff, dense, fine-grained, powdery rock cut by numerous, intersecting quartz veins and sparse veins of kaolinite and alunite of all sizes up to several inches wide (Pl. 8, fig. 1). Infrequent, corroded quartz grains and relict replacements of feldspar are the only visible remnants of original crystallization remaining in the secondary matrix. Intense, local deformation and alteration have destroyed over 85 per cent of the primary constituents even in the least-altered rock of Stage 4. In the most highly altered silicified granodiorite porphyry even the phenocryst outlines are gone.

At places in the silicified granodiorite porphyry zone—especially in the south bank of the 5942 Bench remnant in the bottom of the South Pit and in the adjoining floor of the 5900 Bench—the rock has been intensely broken and crushed prior to recementation by numerous intersecting quartz veins.

PHENOCRYSTS: Quartz in the phenocrysts is the most stable of the original minerals. Possibly half of the exposures of stage 4 retain quartz phenocrysts inherited from the original unaltered porphyry. Where most highly altered however, the original quartz has either been reduced to grains or obscured by introduced vein quartz.

Relict feldspars, containing sericite, fine-

grained quartz, kaolinite, and limonite, with euhedral outlines occur occasionally. Generally, the phenocrysts have been reduced to sericitic aggregates without geometric form by the dispersion of the sericite into the groundmass or the corrosion of the phenocrysts boundaries by the encroachment of the introduced or recrystallized quartz of the groundmass. Although distinguishable feldspar relicts are largely sericite, occasional combinations of sericite and kaolinite seem to preserve the zonal feldspar structures. These zonal pseudomorphs suggest the replacement of the central kaolinite by the marginal sericite. The complete absence of kaolinite in the most highly altered quartz-sericite phases of Stage 4 supports this observation. Ransome (1919, p. 138) has shown that sericite replaces hydrothermal kaolinite in the altered granite of the Ray and Miami districts of Arizona.

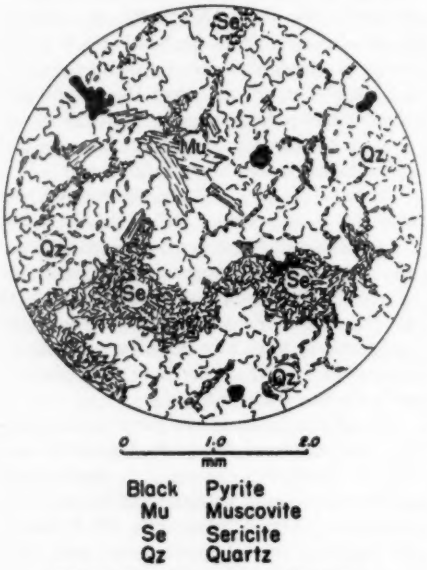


FIGURE 27.—STAGE FOUR—SILICIFIED GRANODIORITE PORPHYRY

The kaolinite and sericite are often scattered indiscriminately through the altered feldspar outlines as irregular aggregates in which the sericite predominates The quartz may develop along linear directions suggestive of the prismatic cleavage of the feldspar. The sericite constitutes most of the alteration on the margins, decreasing sharply to 40 to 50 per cent in the core.

It is doubtful whether any primary minerals are left in the groundmass of the advanced alteration phase of Stage 4. Scattered apatite and magnetite may be the only original constituents and they may be late or post-magmatic in origin. Generally the groundmass of the silicified granodiorite porphyry is a mixture of secondary quartz and sericite in varying proportions. Grain size varies from .003 to .4 mm. The ground mass frequently includes grains as large as 1.0 mm. in diameter that cannot be considered phenocrysts, because they grade regularly down to typical groundmass dimension, .04–.4 mm. Vein quartz grains considered part of the ground mass may reach 1.0 mm. The secondary minerals found in the ground mass with quartz and sericite include kaolinite, chalcedony, hydromica, rare biotite, and orthoclase.

The quartz of the groundmass is the major constituent of the silicified granodiorite porphyry (Fig. 27). It may occur in finely divided anhedral to subhedral non-interlocking grains; fine-grained slightly interlocking crystals suggestive of recrystallization; or as angular and intensely broken and fractured quartz showing intense deformation. Parallel layers of quartz of differing grain size give a banded appearance. Some quartz grains include fluid cavities, .002–.01 mm., in linear orientation. Others include tiny apatite needles .005–.01 mm. long. These may have been inheritied from the original granodiorite porphyry or may have been deposited with the quartz as a late high-temperature vein feature.

In near-by Tyrone, New Mexico, Paige (1922, p. 25) regarded the granodiorite porphyry of most intense alteration as being essentially a quartz-sericite rock. The third and most intense phase of hydrothermal alteration described recently at Castle Dome, Arizona (Peterson, *et al.*, 1946, p. 826) is designated the "quartz-sericite phase." In the final alteration of Stage 4, not only are all traces of phenocrysts destroyed, but even the finely-divided and transported sericite of the groundmass disappears. The final altered granodiorite porphyry becomes

largely an aggregate of recrystallized and introduced quartz grains of groundmass dimensions. The final phase of alteration of the Santa Rita granodiorite porphyry also resembles that described by Spurr (1905, p. 207) in the andesite at Tonopah, Nevada, where the entire mass forms a quartz-sericite aggregate. As alteration increased in intensity, the sericite became less and the secondary quartz more abundant. However, silicification is never quite complete.

Rarely, sericite may compose the entire groundmass with quartz completely absent. Such concentrations of transported sericite have been segregated from adjacent silicified zones. This is an uncommon variety of Stage 4. Veins of cream to buff kaolinite and alunite of mossy and dendritic structure occur occasionally in the groundmass.

Moderately sericitized orthoclase is found on occasion with quartz in graphic intergrowths in the ground mass. The feldspar suggests the late border micrographic intergrowths found at the contacts of the biotite granodiorite porphyry with the aplite in the North Pit. Such occasional occurrences of graphic orthoclase possibly represent relics of late aplite introductions rather than original crystallization of the granodiorite porphyry.

A few scattered magnetite grains were found in a single specimen of silicified granodiorite porphyry taken from a gouge vein, but as a rule magnetite is not found in Stage 4.

Massive chalcedony of late formation occurs as fillings of irregular fissures and cavities. Chalcedony rosettes measuring as much as 2.0 in diameter occur in cavities. The pale-buff, limonite-stained chalcedony shows colloidal banding superimposed on the cryptocrystalline texture. In limited areas it may form as much as 25–35 per cent of the silicified granodiorite porphyry and quartz accounts for 50–60 per cent of the remainder. The prevalence of chalcedony in the overlying Tertiary tuff suggests supergene activity.

Limonite is common, due largely to supergene oxidizing waters. It occurs as veinlets cutting ground mass and relict phenocrysts alike, as tiny specks concentrated in sericite clusters as colloform cavity fillings, as halos about leached sulphide cavity fillings, and as indigenous encrustations within these cavities. Rounded and elongated lenses of limonite .05–.5 mm. long occur locally after pyrite, originally deposited in the cleavage planes of biotite. Cubic pseudomorphs of limonite after pyrite are common.

TABLE 4.—FELDSPAR PHENOCRYST ALTERATION
Santa Rita Stock

Field sample	Geological relations	Per cent* clay minerals		Total per cent clay minerals in feldspar phenocrysts
		K	M	
65	Stage 1		0	0
25-1-K	"		0	0
55	Stage 2	10	10	20
57	"	10	10	20
13	"	20	5	25
15	Stage 2–3			40
	"			50
	"contact"	20	15	50
82	"	30	20	70
16	"		40	50
9	Stage 3	50	20	80
54	"	30	15	
11	"	60	20	

K—Kaolinite.
M—Montmorillonite.
* See note to Table 5.

Argillic development.—The clay mineral content of the feldspar phenocrysts alone and the rock as a whole has been estimated by differential thermal analysis to correlate the clay development in the stock with the arbitrary four stages based on mica degradation. (Fig. 35). Thermal curves were obtained and an estimate of the percentage was made by comparison with curves of known mixtures (Table 4).

Particular attention was directed toward estimating the clay content of representative feldspar phenocrysts from samples of Stages 1, 2, 2–3 "contact", and 3. In Stage 4 the phenocrysts are no longer sufficiently distinct for satisfactory sampling.

The greatest concentration of clay minerals as shown by thermal curves (Kerr and Kulp 1948) is observed in Stage 3 phenocrysts (Table 4). Also, predominance of kaolinite over mont-

TABLE 5.—TOTAL CLAY DEVELOPMENT

Santa Rita Stock

Field sample	Alteration stage	Kaolinite	Per cent* of sample		Clay total
			Montmorillonite	"Illite"	
N-P-2	1	0	0	0	0
73C	1	0	0	0	0
65	1	0	0	0	0
25-1-K	1	0	0	0	0
55	2	5–10	0–5	0	10
57	2	5–10	0–5	0	10
6-26-1P	2	5–10	0	0	10
60	2	5–10	0–5	0	10
13	2 (near 3)	10–15	0–5	0	15
6-26-7P	2 (near 3)	10–15	0–5	0	15
15	3 (near 2)	10–15	5–10	0	20
26-6-W	3 (near 2)	10–15	0	0	15
82	3 (near 2)	15–20	5–10	0–5	25
16	3 (near 2)	5–10	10–15	0–5	25
9	3	25–30	5–10	5–10	40
54	3	15–20	5–10	0–5	30
11	3	30–35	5–10	5–10	45
40	3	15–20	0–5	5–10	25
46D	3	15–20	0–5	5–10	25
42	4 (near 3)	10	0–5	0	10
8-2-P	4	10	0–5	0	10
41	4	5–10	0	0	10
311B	4	0–5	0	0	5
5-20-P	4	0	0	0	0
123	4	0	0	0	0

* Zero indicates that the mineral was not detected. The minimum concentration of montmorillonite and "illite" that could be detected was probably about 5%. The figures 0–5, therefore, indicate that the peaks of these minerals were barely observable. Kaolinite may show a peak in concentration as low as 2%. The total is a rough average and should not be considered more accurate than 5% at best.

morillonite appears in the advanced stages of alteration. Kaolinite is subordinate to absent in the altered igenous rocks in the zinc-bearing areas of mineralization.

A second series of thermal analyses was made combining both phenocrysts and ground mass (Table 5). In these analyses, the ratio of kaolinite to montmorillonite is greater than in the feldspar phenocrysts. Clay of the "illite" type is detected in the Stage 3 samples.

The total argillic content is a maximum in Stage 3. Thin-section study of the alteration stages shows the replacement of clay minerals by sericite and quartz in Stage 4.

Relation of Ore Deposition to Alteration in Santa Rita Stock.—An assay map of recent ore-stripping operations was prepared as a tracing cloth overlay of equal scale to the alteration map. A diagram illustrating the ore and alteration relationships resulting is shown (Fig. 28). Generally speaking, high-ore values occur in zones of Stage 3 alteration or near-by.

The diagram, in reference to progress maps, also shows that more recent operations at Santa Rita have been largely confined to the area of Stage 3 rock. The curved bands superimposed upon the geologic map indicate the area of removal of ore, protore, and waste from

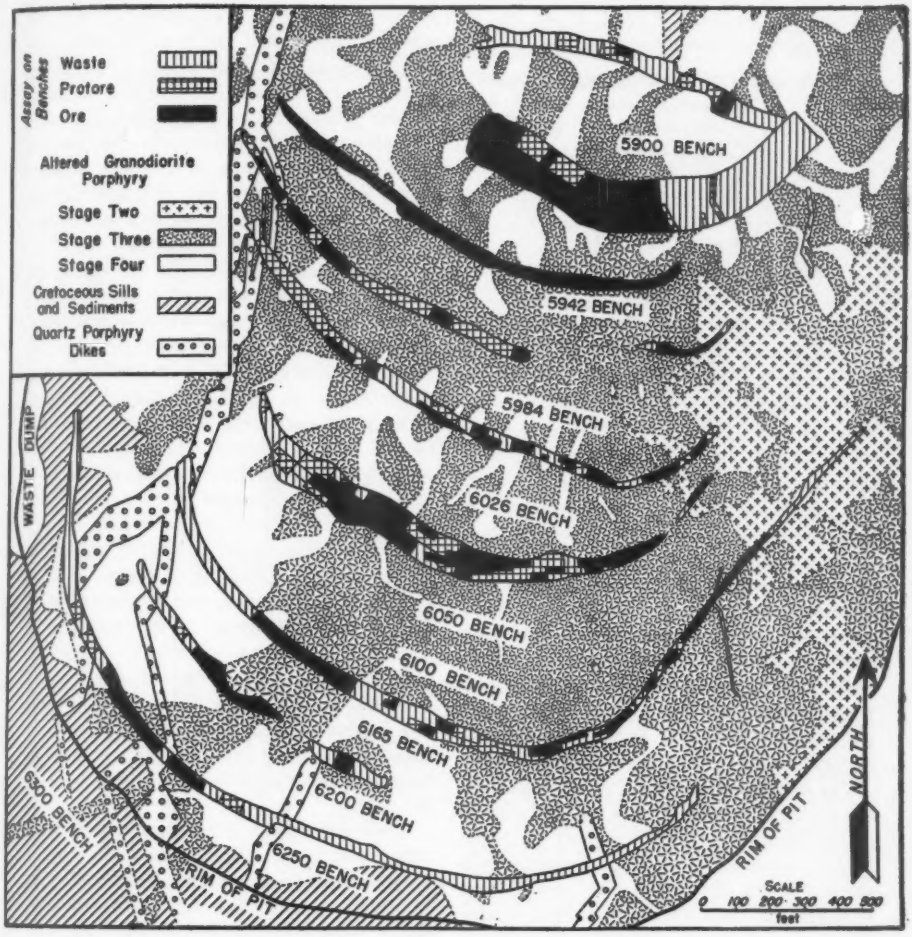


FIGURE 28.—CORRELATION OF ALTERATION STAGES WITH ORE DISTRIBUTION IN THE SOUTH PIT, SANTA RITA, NEW MEXICO

the banks between successive benches during a brief period of operations. Average assay values based on black areas determining ore, protore, and waste within these bands are shown by symbols. With a few exceptions, the areas of Stage 3 hydromica granodiorite porphyry are areas having the assay values of ore and protore. The waste has come generally from areas of Stage 2 biotite granodiorite porphyry, Stage 4 silicified granodiorite porphyry, quartz porphyry dike rock, and marginal sills and sedimentary rocks. The quartz porphyry dike assays ore and protore in some places where bordered by Stage 3.

A correlation of blocks sampled and excavated in the South Pit during the period represented by Figure 28 indicates a strong tendency for ore to favor Stage 3. The division into ore, protore and waste for Stage 2- (32 samples), Stage 3- (836- samples) and Stage 4- (752- samples) is shown below. More precise correlation might be expected if the sampling blocks

The sulphides were introduced along the cleavage planes of the original biotite.

Outlines of completely altered feldspar phenocrysts may be abundant, rare, or absent in Stage 3 porphyry. Unaltered feldspars are not found. Even remnant cores of feldspars are rare in the freshest hydromica granodriorite porphyry. Outlines of euhedral feldspar crystals are common although in most instances the crystals have been completely sericitized (Fig. 26) yet showing ghost plagioclase twinning. The highly altered feldspar contains sericite, kaolinite, and secondary quartz. The altered feldspars range from .4 to 7.5 mm. with most altered phenocrysts .5 to 3.2 mm. They may be deeply embayed and corroded by patches of relatively unaltered, interlocking quartz and orthoclase of the ground mass. When the feldspar has been converted to kaolinite, the outlines of the original crystals remain better defined as the alteration proceeds than if sericite is the main product. Occasionally the altered feldspars show patches of fibrous hydromica with the kaolinite and sericite.

An unusual example of a large zonal feldspar phenocryst measuring 4.8 mm. was found with two included hydromica crystals .9–1.0 mm. in diameter. The original biotite was apparently earlier than the feldspar in the original sequence of crystallization. In the alteration process, the outer feldspar had been changed to kaolinite while the hydromica formed at the expense of the biotite.

Due to absorbed copper stain, euhedral feldspars of the hydromica granodiorite porphyry sometimes appear green when studied in hand specimens. The staining frequently reproduces the zonal banding of the original feldspar. Generally, the feldspar outlines disappear before the outlines of the hydromica are destroyed.

Quartz is an uncommon phenocryst and may be entirely absent, but when present it forms the most stable phenocrysts and may be found as recrystallized grains after the complete destruction of the persistent hydromica. The quartz phenocrysts in Stage 3, when observed, are usually clear, well-rounded, partly-corroded, embayed grains. Stress with recrystallization is frequently shown by wavy extinction. The quartz phenocrysts range in diameter from .5 to 6.5 mm. with the average phenocrysts measuring .5–3.0 mm. Occasionally the larger quartz phenocrysts show a thin marginal halo of sericite alteration .08–.1 mm. wide. The long axes of the grains of sericite are oriented normal to the quartz boundaries. Minute fluid cavities occur oriented in crystallographic directions. Where the quartz is embayed, it is adjacent to the groundmass of quartz and sericitized and kaolinized orthoclase. The corrosion and the rounding of the quartz grains probably occurred during the late magmatic period.

Early in Stage 3, the groundmass may show primary quartz, orthoclase, and occasional biotite. These constituents are absent in the advanced alteration phases of Stage 3. The primary quartz has been recrystallized, the orthoclase and biotite completely destroyed. The secondary constituents of the groundmass are quartz, sericite, kaolinite, hydromica, and limonite.

The orthoclase of the groundmass appears relatively fresh long after the feldspar phenocrysts have been reduced to sericitic aggregates, and sericitized orthoclase in the groundmass can still be identified after the relicts of the feldspar phenocrysts are gone. Knopf (1913, p. 56) noticed selective sericitization of the feldspars in the quartz monzonite wall rock of vein deposits at Marysville, Montana. The orthoclase occurs practically exempt from alteration. Peterson, Gilbert, and Quick (1946, p. 831) noticed this same persistence of primary orthoclase with original quartz in the highly altered quartz monzonite porphyry of the Castle Dome area, Arizona. The orthoclase remains after the oligoclase and biotite have been reduced to pseudomorphous aggregates. Describing the Santa Rita granodiorite porphyry, Landon (1929) observed, "Sericitization has affected the feldspar phenocrysts more than the feldspars of the groundmass." The large feldspar phenocrysts in the freshest rock of the hydromica granodiorite porphyry will show 70–100 per cent alteration to sericite; the associated groundmass feldspars may show but 5 to 20 per cent alteration. Rarely, tiny biotite grains less than .4 mm. occur in the primary quartz and orthoclase of the groundmass. They show absorption from pale brown to deep olive-brown. The biotite of the groundmass is only found in the least-altered hydromica grano-

diorite porphyry. Again the groundmass demonstrates less alteration than the phenocrysts since the large biotite crystals typical of Stages 1 and 2 have been already converted to hydromica. Rare magnetite and zircon grains .2–.4 mm. are found in the freshest porphyry of Stage 3.

Among the secondary constituents of the groundmass, introduced quartz and sericite are the most important. Secondary quartz occurs as fine-grained, rounded, anhedral crystals. These replace orthoclase and primary quartz from which they are distinguished by a lack of interlocking boundaries. Introduced quartz also appears in abundant, intersecting veins that cut both the groundmass and the phenocrysts. In more intense alteration, the amount of secondary quartz and quartz veinlets increases. Recognizable quartz veinlets range from .02 mm. to 5.0–7.5 cm. wide.

The earlier, interlocking quartz grains are generally larger than the introduced quartz and vary from .02 to 1.0 mm. thick. Occasionally a quartz vein shows a double row of interlocking grains indicating simultaneous growth from either side of the fissure. The vein quartz is extremely fresh and free from all inclusions. Even in the limonite-stained capping, the vein quartz remains clear.

Most of the sericite found in the groundmass occurs interstitially among quartz grains. This ubiquitous mineral is also found as fine-grained aggregates and veinlets cutting both the groundmass and the phenocrysts. The sericite is matted, fibrous, and scaly generally measuring .003–.06 mm. thick. Though some sericite has been developed from the orthoclase of the groundmass, most has been derived from the alteration of the feldspar phenocrysts. Eventually all sericite becomes transported as the relict aggregates of feldspar outlines are broken up and the sericite dispersed.

Alteration stage four.—In its most advanced alteration, the Santa Rita intrusive becomes the silicified granodiorite porphyry of Stage 4. Stage 4 is exposed in the South Pit west of the exposures of Stage 3 (Pl. 1). The greatest concentration is in the lowermost benches and on the bottom 5900 Bench of the South Pit (Pl. 8). The occurrence of so much of Stage 4 350 feet below the rim of the pit in these lowermost exposures indicates the hydrothermal character of the alteration.

At the west end of the Central Island, the silicified stage occurs in irregular blocks which extend into both pits on either side of U. S. Highway 180. In the North Pit, it occurs in larger masses, while in the South Pit, it forms irregular marginal fingers intruding the Colorado and Beartooth quartzites. Here the Stage 4 granodiorite porphyry has a marginal occurrence at the contact between the intrusive and the adjoining sedimentary rocks.

A third body occurs as a spindle-shaped linear mass along the southeast wall of the North Pit. This area simulates somewhat the parallel aplite fingers on the northeast benches of the North Pit. On the opposite wall of the North Pit there are four masses of Stage 4 granodiorite prophyry which intrude the metamerphosed sedimentary rocks or lie along their contacts with the Santa Rita intrusive.

The silicified granodiorite porphyry is a light-gray to buff, dense, fine-grained, powdery rock cut by numerous, intersecting quartz veins and sparse veins of kaolinite and alunite of all sizes up to several inches wide (Pl. 8, fig. 1). Infrequent, corroded quartz grains and relict replacements of feldspar are the only visible remnants of original crystallization remaining in the secondary matrix. Intense, local deformation and alteration have destroyed over 85 per cent of the primary constituents even in the least-altered rock of Stage 4. In the most highly altered silicified granodiorite porphyry even the phenocryst outlines are gone.

At places in the silicified granodiorite porphyry zone—especially in the south bank of the 5942 Bench remnant in the bottom of the South Pit and in the adjoining floor of the 5900 Bench—the rock has been intensely broken and crushed prior to recementation by numerous intersecting quartz veins.

PHENOCRYSTS: Quartz in the phenocrysts is the most stable of the original minerals. Possibly half of the exposures of stage 4 retain quartz phenocrysts inherited from the original unaltered porphyry. Where most highly altered however, the original quartz has either been reduced to grains or obscured by introduced vein quartz.

Relict feldspars, containing sericite, fine-

grained quartz, kaolinite, and limonite, with euhedral outlines occur occasionally. Generally, the phenocrysts have been reduced to sericitic aggregates without geometric form by the dis-

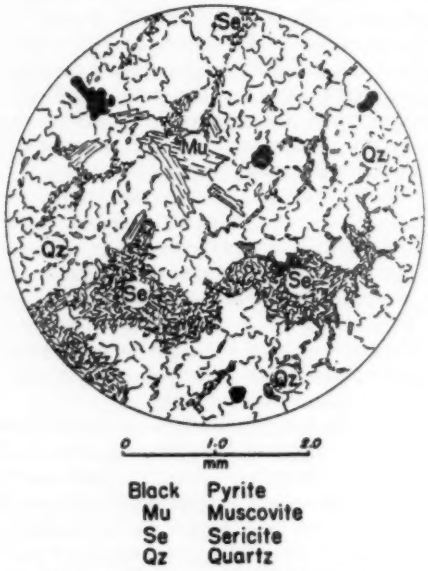


FIGURE 27.—STAGE FOUR—SILICIFIED GRANODIORITE PORPHYRY

persion of the sericite into the groundmass or the corrosion of the phenocrysts boundaries by the encroachment of the introduced or recrystallized quartz of the groundmass. Although distinguishable feldspar relicts are largely sericite, occasional combinations of sericite and kaolinite seem to preserve the zonal feldspar structures. These zonal pseudomorphs suggest the replacement of the central kaolinite by the marginal sericite. The complete absence of kaolinite in the most highly altered quartz-sericite phases of Stage 4 supports this observation. Ransome (1919, p. 138) has shown that sericite replaces hydrothermal kaolinite in the altered granite of the Ray and Miami districts of Arizona.

The kaolinite and sericite are often scattered indiscriminately through the altered feldspar outlines as irregular aggregates in which the sericite predominates The quartz may develop along linear directions suggestive of the prismatic cleavage of the feldspar. The sericite constitutes most of the alteration on the margins, decreasing sharply to 40 to 50 per cent in the core.

It is doubtful whether any primary minerals are left in the groundmass of the advanced alteration phase of Stage 4. Scattered apatite and magnetite may be the only original constituents and they may be late or post-magmatic in origin. Generally the groundmass of the silicified granodiorite porphyry is a mixture of secondary quartz and sericite in varying proportions. Grain size varies from .003 to .4 mm. The ground mass frequently includes grains as large as 1.0 mm. in diameter that cannot be considered phenocrysts, because they grade regularly down to typical groundmass dimension, .04–.4 mm. Vein quartz grains considered part of the ground mass may reach 1.0 mm. The secondary minerals found in the ground mass with quartz and sericite include kaolinite, chalcedony, hydromica, rare biotite, and orthoclase.

The quartz of the groundmass is the major constituent of the silicified granodiorite porphyry (Fig. 27). It may occur in finely divided anhedral to subhedral non-interlocking grains; fine-grained slightly interlocking crystals suggestive of recrystallization; or as angular and intensely broken and fractured quartz showing intense deformation. Parallel layers of quartz of differing grain size give a banded appearance. Some quartz grains include fluid cavities, .002–.01 mm., in linear orientation. Others include tiny apatite needles .005–.01 mm. long. These may have been inheritied from the original granodiorite porphyry or may have been deposited with the quartz as a late high-temperature vein feature.

In near-by Tyrone, New Mexico, Paige (1922, p. 25) regarded the granodiorite porphyry of most intense alteration as being essentially a quartz-sericite rock. The third and most intense phase of hydrothermal alteration described recently at Castle Dome, Arizona (Peterson, *et al.*, 1946, p. 826) is designated the "quartz-sericite phase." In the final alteration of Stage 4, not only are all traces of phenocrysts destroyed, but even the finely-divided and transported sericite of the groundmass disappears. The final altered granodiorite porphyry becomes

largely an aggregate of recrystallized and introduced quartz grains of groundmass dimensions. The final phase of alteration of the Santa Rita granodiorite porphyry also resembles that described by Spurr (1905, p. 207) in the andesite at Tonopah, Nevada, where the entire mass forms a quartz-sericite aggregate. As alteration increased in intensity, the sericite became less and the secondary quartz more abundant. However, silicification is never quite complete.

Rarely, sericite may compose the entire groundmass with quartz completely absent. Such concentrations of transported sericite have been segregated from adjacent silicified zones. This is an uncommon variety of Stage 4. Veins of cream to buff kaolinite and alunite of mossy and dendritic structure occur occasionally in the groundmass.

Moderately sericitized orthoclase is found on occasion with quartz in graphic intergrowths in the ground mass. The feldspar suggests the late border micrographic intergrowths found at the contacts of the biotite granodiorite porphyry with the aplite in the North Pit. Such occasional occurrences of graphic orthoclase possibly represent relics of late aplite introductions rather than original crystallization of the granodiorite porphyry.

A few scattered magnetite grains were found in a single specimen of silicified granodiorite porphyry taken from a gouge vein, but as a rule magnetite is not found in Stage 4.

Massive chalcedony of late formation occurs as fillings of irregular fissures and cavities. Chalcedony rosettes measuring as much as 2.0 in diameter occur in cavities. The pale-buff, limonite-stained chalcedony shows colloidal banding superimposed on the cryptocrystalline texture. In limited areas it may form as much as 25–35 per cent of the silicified granodiorite porphyry and quartz accounts for 50–60 per cent of the remainder. The prevalence of chalcedony in the overlying Tertiary tuff suggests supergene activity.

Limonite is common, due largely to supergene oxidizing waters. It occurs as veinlets cutting ground mass and relict phenocrysts alike, as tiny specks concentrated in sericite clusters as colloform cavity fillings, as halos about leached sulphide cavity fillings, and as indigenous encrustations within these cavities. Rounded and elongated lenses of limonite .05–.5 mm. long occur locally after pyrite, originally deposited in the cleavage planes of biotite. Cubic pseudomorphs of limonite after pyrite are common.

TABLE 4.—FELDSPAR PHENOCRYST ALTERATION
Santa Rita Stock

Field sample	Geological relations	Per cent* clay minerals		Total per cent clay minerals in feldspar phenocrysts
		K	M	
65	Stage 1		0	0
25-1-K	"		0	0
55	Stage 2	10	10	20
57	"	10	10	20
13	"	20	5	25
15	Stage 2–3			40
	"			50
	"contact"	20	15	50
82	"	30	20	70
16	"		40	50
9	Stage 3	50	20	80
54	"	30	15	
11	"	60	20	

K—Kaolinite.
M—Montmorillonite.
* See note to Table 5.

Argillic development.—The clay mineral content of the feldspar phenocrysts alone and the rock as a whole has been estimated by differential thermal analysis to correlate the clay development in the stock with the arbitrary four stages based on mica degradation. (Fig. 35). Thermal curves were obtained and an estimate of the percentage was made by comparison with curves of known mixtures (Table 4).

Particular attention was directed toward estimating the clay content of representative feldspar phenocrysts from samples of Stages 1, 2, 2–3 "contact", and 3. In Stage 4 the phenocrysts are no longer sufficiently distinct for satisfactory sampling.

The greatest concentration of clay minerals as shown by thermal curves (Kerr and Kulp 1948) is observed in Stage 3 phenocrysts (Table 4). Also, predominance of kaolinite over mont-

TABLE 5.—TOTAL CLAY DEVELOPMENT

Santa Rita Stock

Field sample	Alteration stage	Kaolinite	Per cent* of sample		Clay total
			Montmorillonite	"Illite"	
N-P-2	1	0	0	0	0
73C	1	0	0	0	0
65	1	0	0	0	0
25-1-K	1	0	0	0	0
55	2	5–10	0–5	0	10
57	2	5–10	0–5	0	10
6-26-1P	2	5–10	0	0	10
60	2	5–10	0–5	0	10
13	2 (near 3)	10–15	0–5	0	15
6-26-7P	2 (near 3)	10–15	0–5	0	15
15	3 (near 2)	10–15	5–10	0	20
26-6-W	3 (near 2)	10–15	0	0	15
82	3 (near 2)	15–20	5–10	0–5	25
16	3 (near 2)	5–10	10–15	0–5	25
9	3	25–30	5–10	5–10	40
54	3	15–20	5–10	0–5	30
11	3	30–35	5–10	5–10	45
40	3	15–20	0–5	5–10	25
46D	3	15–20	0–5	5–10	25
42	4 (near 3)	10	0–5	0	10
8-2-P	4	10	0–5	0	10
41	4	5–10	0	0	10
311B	4	0–5	0	0	5
5-20-P	4	0	0	0	0
123	4	0	0	0	0

* Zero indicates that the mineral was not detected. The minimum concentration of montmorillonite and "illite" that could be detected was probably about 5%. The figures 0–5, therefore, indicate that the peaks of these minerals were barely observable. Kaolinite may show a peak in concentration as low as 2%. The total is a rough average and should not be considered more accurate than 5% at best.

morillonite appears in the advanced stages of alteration. Kaolinite is subordinate to absent in the altered igenous rocks in the zinc-bearing areas of mineralization.

A second series of thermal analyses was made combining both phenocrysts and ground mass (Table 5). In these analyses, the ratio of kaolinite to montmorillonite is greater than in the feldspar phenocrysts. Clay of the "illite" type is detected in the Stage 3 samples.

The total argillic content is a maximum in Stage 3. Thin-section study of the alteration stages shows the replacement of clay minerals by sericite and quartz in Stage 4.

Relation of Ore Deposition to Alteration in Santa Rita Stock.—An assay map of recent ore-stripping operations was prepared as a tracing cloth overlay of equal scale to the alteration map. A diagram illustrating the ore and alteration relationships resulting is shown (Fig. 28). Generally speaking, high-ore values occur in zones of Stage 3 alteration or near-by.

The diagram, in reference to progress maps, also shows that more recent operations at Santa Rita have been largely confined to the area of Stage 3 rock. The curved bands superimposed upon the geologic map indicate the area of removal of ore, protore, and waste from

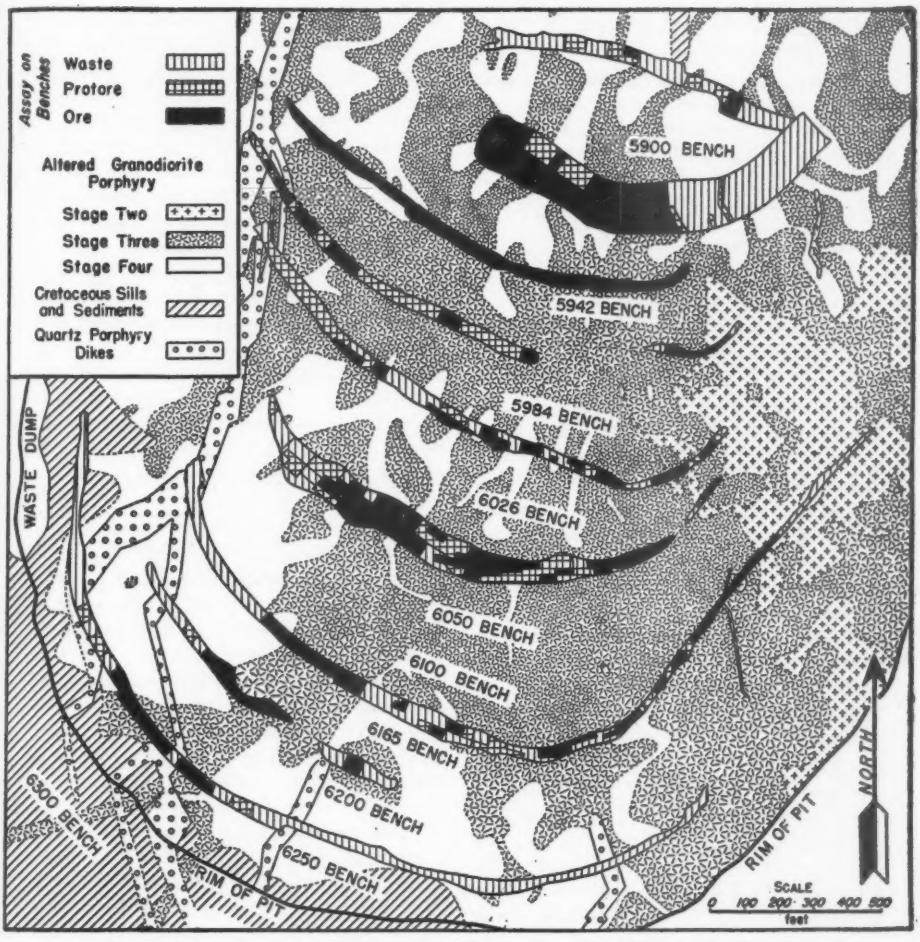


FIGURE 28.—CORRELATION OF ALTERATION STAGES WITH ORE DISTRIBUTION IN THE SOUTH PIT, SANTA RITA, NEW MEXICO

the banks between successive benches during a brief period of operations. Average assay values based on black areas determining ore, protore, and waste within these bands are shown by symbols. With a few exceptions, the areas of Stage 3 hydromica granodiorite porphyry are areas having the assay values of ore and protore. The waste has come generally from areas of Stage 2 biotite granodiorite porphyry, Stage 4 silicified granodiorite porphyry, quartz porphyry dike rock, and marginal sills and sedimentary rocks. The quartz porphyry dike assays ore and protore in some places where bordered by Stage 3.

A correlation of blocks sampled and excavated in the South Pit during the period represented by Figure 28 indicates a strong tendency for ore to favor Stage 3. The division into ore, protore and waste for Stage 2- (32 samples), Stage 3- (836- samples) and Stage 4- (752- samples) is shown below. More precise correlation might be expected if the sampling blocks

were smaller. As the data stand, 81 per cent of Stage 3 samples were ore or protore.

CORRELATION BETWEEN ORE VALUES AND ALTERATION STAGES

Ore	*Protore*	*Waste*
	Stage 2 (32 samples)	
14	5	13
	Stage 3 (836 samples)	
483	194	159
	Stage 4 (752 samples)	
262	77	413

The history of development indicates a correlation between the stages of alteration of the granodiorite porphyry and the continuity of operations. The North Pit, excavated principally in the slightly altered granodiorite porphyry of Stages 1 and 2, has not been in operation since 1927. In the South Pit, where mining operations have continued since the opening of the pits in 1910 (except for the depression years of the early 1930's), the granodiorite porphyry containing the copper ore is principally of Stage 3 and near-by Stage 4 of alteration. The stripping operations have been extended south along the zone of greatest alteration shown by the prominent southward bulge of the South Pit and its benches. The central core of the stock represented in the South Pit by biotite granodiorite porphyry of Stage 2 on the southeast wall has been much less extensively mined.

The correlation has been further verified by the microscopic study of all of the thin sections of specimens from different parts of the Santa Rita intrusive. While no sampling program was attempted, the distribution was broad enough to indicate a trend. Specimens of Stage 3 were found to contain more pyrite and chalcocite than those of the other zones. Pyrite appeared to be a late introduction in Stage 1 of alteration and apparently replaced the earlier magnetite. The ore values obtained originally in Stage 1 granodiorite porphyry were apparently derived from oxidized copper deposits and fissure fillings of chalcocite rather than from the disseminated grains of chalcocite that constitute the bulk of the ore in the South Pit.

Originally it was thought that the degree of economic mineralization was a direct function of alteration. Describing the Comstock Lode, Becker (1882, p. 210) demonstrated that mineralization in the form of pyrite was proportional in amount to degree of alteration. There is no reason to doubt that the hydrothermal solutions at Santa Rita were largely mineralizing solutions and that the corrosion and leaching of the primary rock-forming elements was necessary to prepare the cavities and pores in which the later sulphides of iron and possibly copper were deposited. But the most highly altered granodiorite porphyry of Stage 4 does not produce the highest ore values.

Disseminated Sulphides:—Pyrite occurs as disseminated grains in the least-altered granodiorite porphyry of Stage 1. It is a prominent mineral throughout Stages 2 and 3 and most of Stage 4. It is abundant in sediments bordering the intrusive. In the highly altered silicified granodiorite porphyry, pyrite has been removed by post-mineral solutions, destroyed through late recrystallization, or in places completely altered to limonite.

Disseminated chalcocite is absent in the least-altered granodiorite porphyry, appears in the more altered porphyry of Stage 2, occurs prominently in Stage 3, and is observable in Stage 4, although scarce in the most highly silicified granodiorite porphyry.

An indication of the prevalence of pyrite and chalcocite in each of the four stages of alteration is obtainable by listing slides containing these minerals from among 160 thin sections of specimens collected within the intrusive (Fig. 29).

Pyrite formed as a late mineral in the highly mineralized zones of Stage 1, in a third of the slides of Stage 1 porphyry, in a half of the slides of Stage 2, in nearly two-thirds of the slides of Stage 3, and in half of the slides of Stage 4.

Chalcocite was not found in Stage 1. In Stage 2, about a quarter of the thin sections contained chalcocite. It was found in three-fifths of the slides of Stage 3, and in less than a third of the slides of Stage 4.

MINERALS: Pyrite occurs in disseminated grains as aggregates and in veinlets. Individual grains are euhedral (both in cubes and pyritohedra) to anhedral, skeletal, and angular. Pyrite grains range from .04 to 2.0 mm. thick and may or may not show marginal replacement by chalcocite.

Pyrite veinlets, ranging up to 3.0 mm. wide, cut through all other minerals of the grano-

diorite porphyry, cutting linear structures of biotite, sericite, and quartz bands found in some phases of the granodiorite. This indicates that the introduction of pyrite followed the un-

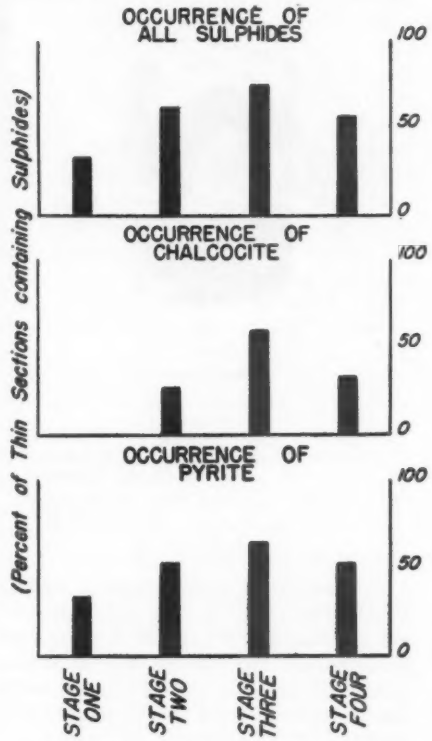


FIGURE 29.—PREVALENCE OF SULPHIDE IN ALTERATION STAGES

common, linear orientation of the granodiorite and the hydrothermal alteration of the original phenocrysts to sericite. Pyrite veinlets occur with infrequent borders of chalcocite or in symmetrical veins showing both earlier and later quartz.

Pyrite occurs as elongated lenses occupying the former cleavages of the relict phenocrysts. The original partings and cleavages were still the main avenues for the introduction of mineralizing solutions. The pyrite in places favors the cleavages of old, corroded hornblende altered to chlorite, biotite altered to chlorite and hydromica, and feldspar phenocrysts reduced to aggregates of sericite and kaolinite.

Spurr (1905, p. 207) described similar occurrences of pyrite following the outlines of the marginal hornblende and biotite of the altered Tonopah, Nevada, andesite. Massive partial

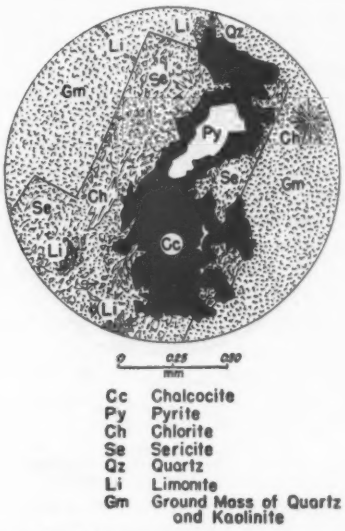


FIGURE 30.—MARGINAL REPLACEMENT OF PYRITE GRAIN BY CHALCOCITE

replacements of the feldspars at Breckenridge, Colorado, (Ransome, 1911, p. 100) and of ferromagnesian minerals similar to those of altered hornblende found in the Comstock Lode district (Becker, 1882, p. 210) are occasionally observed. The pyrite reproduces the crystal outlines but is not confined to the cleavage traces or the marginal portions of the crystals.

Chalcocite grains may have the outlines, texture, and habits of the pyrite they replace. The grains are often found as a marginal replacement of pyrite (Fig. 30).

All stages from a thin film of incipient replacement to a wide border of chalcocite or complete conversion may be found in a single specimen.

Veinlets of pyrite completely replaced by chalcocite are found up to .4 mm. wide. As replacements of pyrite veinlets, the chalcocite veinlets also cut both phenocrysts and groundmass of the porphyry. Chalcocite veinlets formed along fractures in larger veins of pyrite (Fig. 31). In large veins, pyrite exhibits intri-

cate fracture patterns which have permitted the influx of chalcocite-precipitating solutions. The chalcocite replaces the pyrite outward from the fracture which is the initial locus of deposition.

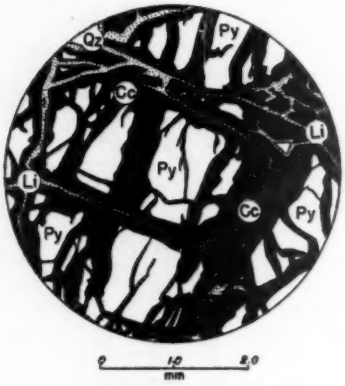


FIGURE 31.—REPLACEMENT OF PYRITE BY CHALCOCITE

Since pyrite replacement of phenocrysts may be observed, similar chalcocite replacements might be expected. Such replacements are rare but have been observed. The phenocrysts must first have been replaced by pyrite and then the pyrite, included in the phenocryst, must have been replaced by chalcocite. An altered feldspar phenocryst shows partial replacement by chalcocite after earlier pyrite (Fig. 32). Preservation of crystal boundaries is due to the introduced sulphide.

Late in Stage 1, pyrite is found replacing the earlier magnetite grains typical of both the Hanover and the least altered Santa Rita granodiorite porphyry. All unaltered granodiorite contains magnetite presumably of late magmatic origin. With increased alteration, the magnetite gives way to pyrite in Stages 1 and 2. In the altered phases of Stage 2 biotite granodiorite porphyry, pyrite finally excludes the magnetite. Much of the pyrite was undoubtedly deposited directly from the mineralizing solutions without replacing magnetite.

Schwartz (1939, p. 200) observes:

"In the early stages (of hydrothermal alteration) at least, pyrite seems to form by the combination of iron of the ferro-magnesian minerals with sulphur from the hot solutions. Magnetite also contributes its quota of iron. With more intense alteration, pyrite may replace practically any mineral."

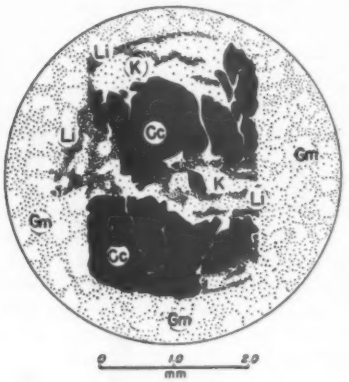


FIGURE 32.—FELDSPAR PHENOCRYST ALMOST COMPLETELY REPLACED BY CHALCOCITE IN STAGE THREE

The least-altered quartz monzonite from the Boulder batholith at Butte contained as much as 1.25% magnetite and only .04% pyrite. After alteration, the magnetite had disappeared completely and the pyrite content had risen at the expense of magnetite to 4–6% (Weed, 1912, p. 91).

Landon (1929) described the magnetite of the Santa Rita-Hanover-Fierro area as always forming "earlier than any sulphide."

Criteria pointing to replacement of the magnetite by pyrite or the earlier origin of the oxide at Santa Rita are:

1. Rarely, tiny grains show cores of magnetite replaced marginally by pyrite.
2. Pyrite veinlets cut magnetite veinlets.
3. Magnetite and pyrite are generally observed to be mutually exclusive.
4. Magnetite is characteristic of the least-altered granodiorite porphyry while pyrite is characteristic of the altered phases.
5. Magnetite grains are more intensely fractured than the pyrite.

The first of the chalcocite is associated with the later phases of Stage 2. Much of it has obvi-

ously been formed by replacement of the earlier pyrite. All stages of partial to complete replacement are found. In addition, some of the chalcocite may have been deposited directly by the reduction of copper sulphate solutions. A number of polished sections were examined. Most were examples of disseminated ore but massive vein chalcocite was also represented. All sections showed chalcocite replacing pyrite. The chalcocite in each case was mottled with covellite in a texture and relationship suggesting supergene replacement. Etching with 1:1 HNO_3 brought out the characteristic supergene texture (Schneiderholm, 1922, Van der Veen, 1925) in several sections. In the other sections the grains were too small or too thoroughly mottled with covellite to give clear etch patterns. Cuprite, native copper, and malachite were all observed to be later than the chalcocite.

Ore genesis.—At the beginning of the century, Emmons (1901) and others called attention to the supergene enrichment of sulphide ore bodies at and below the water table. The solution of metallic minerals in the oxidized zone and subsequent precipitation below the water level with resulting enrichment was recognized as applying to many copper deposits, particularly in the western United States.

Santa Rita was one of the localities visited by Emmons (1901, p. 450). He judged, "that most of the ore had been formed by leaching down from the low-grade pyritous body in the limestones which once covered the porphyry." This concept has apparently continued (Bateman, 1942, p. 274).

One essential in the process of supergene sulphide enrichment is oxidation. Without decomposition of the original sulphides at the surface and their transportation downward in solution, deposition at or below the water table would not take place. At Santa Rita, large oxidized areas are well exposed, particularly along several of the upper benches in the South Pit. The bordering sedimentary formations and the sill rocks have also suffered leaching near the surface as indicated by the distribution of limonite and occasional traces of oxidized copper minerals. Cubic cavities furnish evidence of the oxidation and removal of pyrite.

Another essential to supergene sulphide enrichment is a suitable original source mineral to provide the copper. At Santa Rita, chalcopyrite and cupriferous pyrite have been suggested. If chalcopyrite were the generating mineral, at least some remnants might be expected in the oxidized zone. These were not observed during the field studies and Mr. Gerald J. Ballmer, who has observed the deposit over a number of years, confirms the absence of chalcopyrite in both the North and South Pits. Also chalcopyrite was not reported at the concentrator. A single occurrence in one of the least-altered portions of the South Pit is reported, but the locality was not relocated in this study. A core obtained in 1947 from several hundred feet beneath the surface on the south side of the South Pit shows chalcopyrite associated with garnet apparently from a small contact zone. In the pit area itself, however, either (1) chalcopyrite was completely destroyed during the process of supergene enrichment; or (2) it was not abundant enough to yield solutions charged with adequate copper to form the present ore body; or (3) it was emplaced much higher than the present erosion level.

The occurrence of copper as minute intergrowths of chalcopyrite in pyrite or as substitution of copper ions in the pyrite lattice is open to several objections. Microscopic study of pyrite fails to reveal inclusions of chalcopyrite. Thus any appreciable copper content of pyrite revealed by analysis would presumably be part of the pyrite lattice, and an analysis of pyrite from the South Pit showed only .025 per cent copper. Further spectrographic analyses indicated only traces of copper. Also copper should not be expected to substitute in the pyrite lattice to any appreciable extent because of its large ionic radius compared with iron. Such substitution has never been reported to any significant extent (Dana, 1944).

Chalcopyrite has been found, but beyond the pit areas, in drilling operations in the limestone area north of the North Pit. It occurs in replacement zones along with pyrite and magnetite and is quite free from oxidation. Presumably such replacement bodies could have existed at one time in the sedimentary cover above the area of the present Pits.

The fact that the ore follows the periphery of the stock, including important apophyses, and that it is closely related to the hydrothermal alteration pattern rather than forming a horizontal sheet would indicate that the Santa Rita

deposit is not a normal case of secondary sulfide enrichment.

Two most probable hypotheses are left. One attributes the present ore body to hypogene deposition modified by some secondary sulfide enrichment. The other theory would make the Santa Rita deposit almost entirely a supergene product.

The partial hypogene theory presumes alteration and pyritization of the Santa Rita stock and the marginal formations. Subsequently, hypogene solutions carrying copper followed the same ore channels as the alteration solutions and replaced the pyrite with chalcocite. A modification allowed certain other copper minerals such as chalcopyrite to be formed initially but later altered to the final product, chalcocite. Secondary sulfide enrichment has modified the distribution but only to the extent of enrichment of the upper part. The relation of hydrothermal alteration to mineralization has not been obliterated.

This theory accounts for the present distribution of the ore in the stock and in the country rock. However, high-temperature replacement of pyrite by chalcocite without any evidence of other high-temperature copper sulfides such as chalcopyrite and bornite seems strange. The polished sections of ore studied showed the typical covellite-chalcocite mottling of supergene replacement. Covellite is so formed under oxidizing conditions which are not consistent with the reducing nature of a high-temperature sulfide environment. Etch patterns produced on three of the specimens were characteristic of low-temperature chalcocite. Metallic copper and cuprite found at the bottom of the South Pit indicate the depth of supergene activity. These objections do not invalidate this theory but further evidence will be required.

The supergene theory postulates a copper ore body far above the present surface level. Since the area must have once been covered by a mile of sedimentary material in order to produce the Colorado shale (Hedberg, 1936), an estimate of half a mile for the original vertical extension of the ore body is justifiable. Intensive weathering and erosion, which caused peneplanation before the Tertiary lavas covered the area, plus the post-volcanic erosion was sufficient to leach the entire copper deposit above and carry the metallic ions downward. The present distribution of the ore body and its close relationship to alteration may be said to be due to the fact that Stage 3 rock is most porous and contains the greatest concentration of the copper-precipitating agent pyrite. On this theory, chalcopyrite is not common in the altered pyritized rocks of the pit because the temperature was too high. Therefore pyrite was deposited at this level and the chalcopyrite was carried above. The supergene copper-bearing solutions would follow the path of least resistance and would precipitate chalcocite in porportion to the concentration of pyrite in the rocks.

A serious objection to this theory is the lack of evidence of marginal chalcopyrite immediately adjacent to the pit. If this temperature effect was the important one, some chalcopyrite should have formed far out from the stock along major fractures. In answer, it can be pointed out that some chalcopyrite has been found beyond the pit areas and that the alteration pattern indicates that the movement of the solutions was largely vertical.

On this theory, the decrease in copper values in Stage 4 silicified granodiorite porphyry is due to the decrease in pyrite content and porosity, both factors being a result of the silification factor.

Certain practical implications are to be derived from consideration of the two theories of ore genesis. Most important is the expectable vertical extent of ore. If the hypogene phase is more importaht than heretofore assumed, copper mineralization may be found at greater depths than if the unmodified supergene theory is valid.

Hornblende Porphyry Dikes

The hornblende porphyry dikes of the Ground Hog and Hanover areas in places have undergone an early epoch of epidotization prior to the formation of clay minerals.

Epidote occurs as: (1) a granular dull-green variety and (2) a bladed light-green type which often forms rosettes of radiating crystals. Granular epidote is common where alteration is intense; the bladed variety characterizes less altered rock, although the two may occur together. In most dikes the amount of epidote varies widely from point to point, usually

abundant for a few feet along the borders, where the igneous texture may be destroyed, but sparse or lacking within the dike except along shear zones. Some dikes, for example the Eta dike in the Empire Zinc mine, are completely epidotized throughout.

Like epidote, chlorite is a characteristic alteration mineral of the dikes. It is developed principally in fracture zones within dikes or at their margins, although microscopic study indicates that chlorite is of wider distribution than might be expected from megascopic observation. Chloritized shear zones are usually bordered by epidotized granodiorite porphyry.

Where epidote and chlorite are not well developed, the granodiorite porphyry may appear quite fresh in hand specimens, although micro-

TABLE 6.—SUMMARY OF THE SEQUENCE OF MINERALIZATION

1. *Early phases*
   - A. *Early quartz deposition*
     1. Networks of early quartz veins cut the granodiorite porphyry.
     2. Early quartz veins are cut by magnetite, hematite, pyrite, and chalcocite veins; aplites and quartz porphyry dikes.
   - B. *Magnetite and hematite deposition*
     1. Irregular grains and euhedral crystals of magnetite occur as late disseminations and minute, cross-cutting veins in the least altered granodiorite porphyry.
     2. Massive magnetite and hematite bodies replace the metamorphosed Syrena formation along and near the intrusive contact.
     3. Magnetite cements granodiorite porphyry and metamorphosed sedimentary fragments in the Whim Hill breccia.
     4. Magnetite and hematite veins cut early quartz veins.
     5. Magnetite occurs partly replaced by later pyrite.
     6. Hematite bodies occur cut by ramifying networks of later quartz, kaolinite, pyrite, and chalcocite.
   - C. *Aplite injection*
     1. Aplite is found as dikes and layers cutting cutting biotite granodiorite porphyry of Stage 2 and silicified granodiorite porphyry of Stage 4.
     2. Aplite dikes cut both fragments and matrix of the Whim Hill breccia.
   - D. *Early pyrite deposition*
     1. Pyrite veins are found cutting granodiorite porphyry and earlier quartz veins.
     2. Early pyrite veins are interrupted by cross-cutting quartz prophyry dikes.
     3. Pyrite occurs as marginal replacements of magnetite grains disseminated in the granodiorite porphyry.
     4. Disseminated pyrite and earlier magnetite in the granodiorite porphyry are mutually exclusive.
     5. Pyrite replaces magnetite beds in the Syrena formation.
     6. Pyrite veins cut magnetite beds and replacement bodies in the sedimentary rock formations.
     7. Pyrite veins cut the hematite replacement body at the igneous contact.

TABLE 6.—*Continued*

2. *Quartz porphyry dikes*
3. *Late phases*
   - A. *Late quartz deposition*
     1. Aside from the evidence given under (1-A) above, some quartz veins may be followed from the granodiorite porphyry into the quartz porphyry dikes.
     2. Quartz veins appear along the margin of the quartz porphyry dike indicating contemporary or subsequent deposition.
     3. Quartz rarely occurs as the central deposit in a symmetrical vein of pyrite and quartz.
   - B. *Late pyrite deposition*
     1. Pyrite veins of late deposition may be traced from the granodiorite porphyry into the quartz porphyry dikes.
   - C. *Chalcocite deposition (hypogene and supergene)*
     1. Chalcocite occurs most frequently as marginal replacements of disseminated pyrite grains in the altered granodiorite porphyry.
     2. Chalcocite forms as blue-black pseudomorphs after pyrite. Cubes and pyritohedra, now chalcocite, are found.
     3. Chalcocite-pyrite veins are found occasionally cutting quartz porphyry dikes.
     4. Chalcocite veins cut all structures of known primary deposition.
     5. Chalcocite has been found as a late deposit in banded veins of quartz, kaolinite and pyrite cutting the hematite body in the Syrena formation.
     6. Leached zones occur near the surface from which copper values—presumably from chalcocite—have been removed.

scopic study may show it to be partly altered. Most biotite is replaced by chlorite and epidote, although the accompanying hornblende may be fresh. Scattered grains of epidote are common and the feldspar phenocrysts are usually clouded with sericite.

Epidote is abundant in altered zones and may replace any rock-forming mineral. Some specimens contain only epidote with minor amounts of calcite. Chlorite replaces biotite and hornblende, and secondary silica occurs in some specimens. Calcite is common as veinlets and irregular masses particularly along dike margins, probably because of assimilation of adjacent limestone by the granodiorite magma, or introduction from hydrothermal solutions rising along the contact.

The feldspar phenocrysts are partly altered to sericite, epidote, and montmorillonite. The predominance of montmorillonite over kaolinite is in distinct contrast to the feldspar alteration in the area of copper mineralization where kaolinite is prominent (Table 7).

Since the original feldspars are the same in the dikes as in the stock at Santa Rita, i.e. oligoclase, the contrasting argillic alteration emphasizes the difference in the physio-chemical nature of the solutions associated with the different metallic content. The zinc-bearing solutions produced epidote, serpentine, garnet, and montmorillonite predominantly, the copper-bearing solutions gave quartz, sericite, and kaolinite. This observation is substantiated by the fact that the masses of clay found in vugs and fractures in the Santa Rita area are kaolinite but the masses in the zinc areas are montmorillonite. Although information is insufficient to reconstruct the precise composition of the different hydrothermal solutions, it seems reasonable that the Santa Rita solutions were of higher temperature and pH but lower in calcium and magnesium content.

Thermal analyses of dike specimens from the Ground Hog Mine indicate that the amount of montmorillonite plus "illite" present, increases toward ore bodies. (Table 8). There was also 10–20 per cent of kaolinite in the specimens analyzed but it appeared independent of proximity to the ore body and is probably due to supergene effects.

In the Hanover area a close relationship is apparent between epidotization of hornblende granodiorite dikes and zinc mineralization. Epi-

TABLE 7.—FELDSPAR ALTERATION IN ZINC AREAS

Sample	Geological relationships	Clay minerals per cent by weight	
		M	K
1-Oswaldo	From gamma-dike in fault zone ore channel	75	0
2-Oswaldo	From gamma-dike in fault zone ore channel (different drift)	75	20
33C-Hanover	4th level	30	0
77-56-Hanover	Distant from ore	10	0
30-9-Hanover	Distant from ore	20	0
30-8-Hanover	Distant from ore	20	0

M—Montmorillonite.
K—Kaolinite.

TABLE 8.—FELDSPAR ALTERATION AND ORE PROXIMITY

Ground Hog Mine

Sample	Geological relationships	Clay minerals per cent by weight		Total 3-layer lattice clay minerals
		M	I	
66C	NW end Black dike immediately associated with ore 1200′ level	70	20	90
63C	40′ from hanging wall of ore channel 1800′ level	60	15	75
65C	Est. 50–100′ from ore channel 1400′ level	40	10	50
68C	200′ in white dike at Delta fault, ore channel 100′ 1200′ level	40	0	40
67C	Middle of Black dike, 120′ to ore channel, 1200′ level	20	20	40
59C	200′ from ore channel, 1800′ level	20	0	20

M—Montmorillonite.
I—"Illite".

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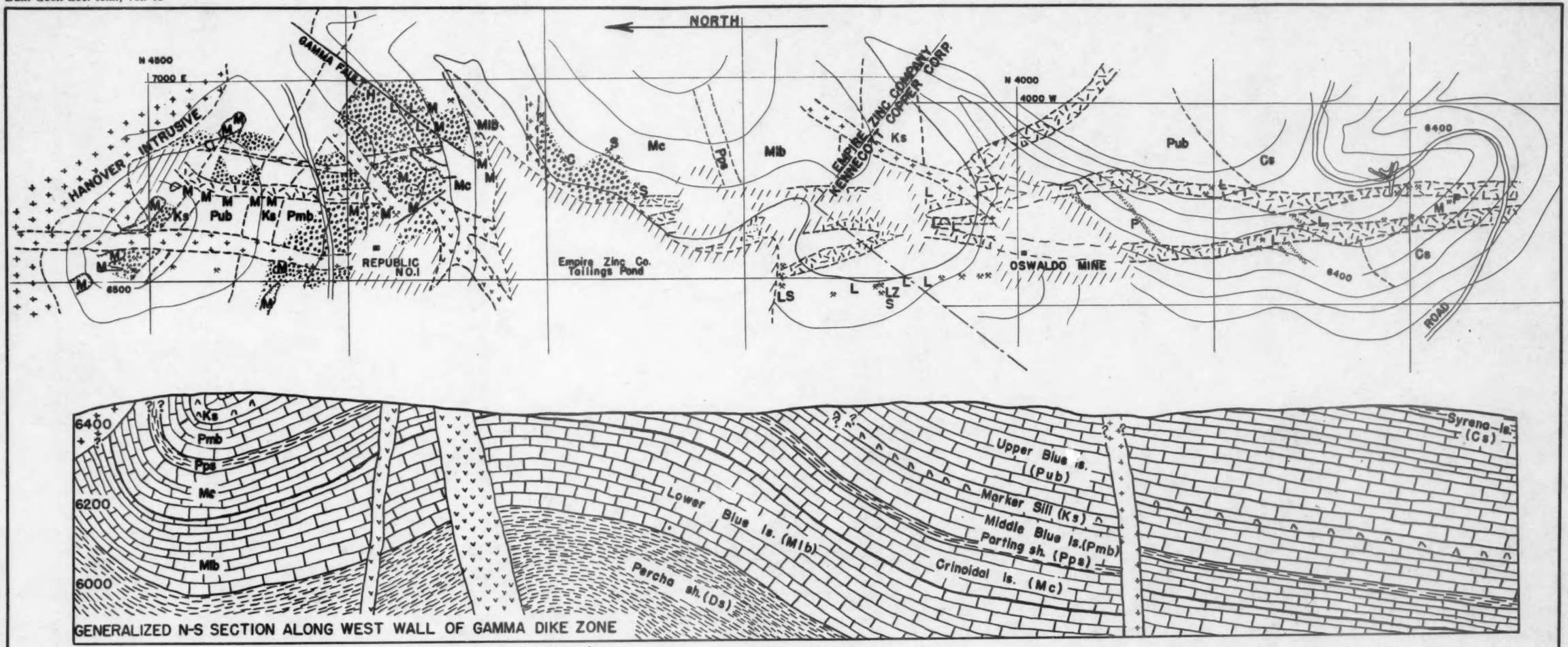

PLAN AND GENERALIZED NORTH-SOUTH SECTION ALONG WEST WALL OF GAMMA DIKE ZONE

dotization is accompanied by development of sphalerite and contact silicate minerals in adjacent limestones, particularly along the hanging wall. Where an epidotized dike is bordered by the Crinoidal limestone, commercial ore bodies are common. In many places the dike itself is mineralized, with sphalerite occurring in an epidote gangue. The Eta dike in the 610 stope of the Empire Zinc mine is thus mineralized to form commercial ore.

In the Ground Hog mine where the dikes and ore bodies are less regular, the correlation between epidotization and mineralization is not so striking, but a general increase in epidote is noted toward an ore body.

Epidote usually occurs in pre-ore dikes along which zinc ore bodies have been developed; therefore, the presence of the mineral suggests that the dike has been altered by ore-forming solutions. In prospecting, surface occurrences of epidote in pre-ore dikes are favorable indications of zinc replacement in appropriate limestone beds. However, the extent of epidotization at any point is a somewhat uncertain guide to the intensity of mineralization or distance to a possible ore body. A study was made of surface epidote occurrences along the Gamma dike from the Republic No. 1 shaft of the Empire Zinc Company southward for 3400 feet to the southern boundary of the Kennecott Copper Corporation Oswaldo property. Along this line the Crinoidal limestone dips to the south, and known ore bodies lie at progressively greater depths southward along the Gamma dike. Near the Republic No. 1 shaft, ore bodies are immediately below the surface; on the south end of the Oswaldo claim they are 450 feet below the surface. Epidote in varying amounts was observed in the dike but there seems to be no consistent variation in intensity of epidotization along the strike. Here it is apparent that epidote is concentrated in certain parts of the dike, usually near the margins or along shear zones. Therefore, at the surface where observations must be based on incomplete exposures or on float derived from any part of the dike cross section it is difficult to make any estimate of the overall dike alteration.

Quartz Porphyry Dikes

General statement.—The type of alteration imposed upon quartz granodiorite dikes depends on the age relationship between the dikes and local zinc mineralization. In the Ground Hog mine, mineralization followed emplacement of both hornblende porphyry and quartz porphyry dikes. Both types of dikes have been affected by the epidote alteration which accompanied mineralization. This alteration has been discussed in the preceding section. In the Hanover area, hornblende porphyry dikes were emplaced before zinc mineralization, whereas the quartz porphyry dikes as a rule followed mineralization. Here the alteration of pre-ore dikes is due largely to mineralizing solutions and is of the epidote type. The quartz porphyry dikes, on the other hand, are affected by a later and different alteration. Hornblende porphyry dikes are lacking at Santa Rita, hence no direct comparison in the type of alteration can be made.

Hanover group.—Alteration in quartz porphyry dikes of the Hanover area is not striking in hand specimen, although it is apparent that the rock is not entirely fresh. The plagioclase phenocrysts are soft and white, sometimes with a greenish tinge. In contrast, orthoclase crystals are pink and fresh. Biotite is dull-green and lustreless. The rock effervesces in acid. These features characterize specimens regardless of their location with respect to the dike borders. Alteration, therefore, extends across the dike as a whole and is not concentrated in certain parts of the cross section, as in the hornblende porphyry dikes.

The characteristic alteration minerals are sericite, calcite, muscovite, chlorite, secondary silica, and minor epidote. Sericite replaces plagioclase phenocrysts and usually occurs throughout the groundmass. The andesine grains in various specimens contain from 60 to more than 90 per cent sericite, usually the latter. Orthoclase is relatively unaltered. Calcite is widely distributed and occurs as irregular masses in the groundmass or as a replacement of early-formed minerals. Muscovite is the typical alteration of biotite and hornblende. Chlorite may also replace the ferromagnesian minerals, and in a few specimens chlorite replaces muscovite.

Silicification is apparent in most specimens. The groundmass contains amoeboid quartz grains which are flecked with alteration material and inclusions of the groundmass. The grains of

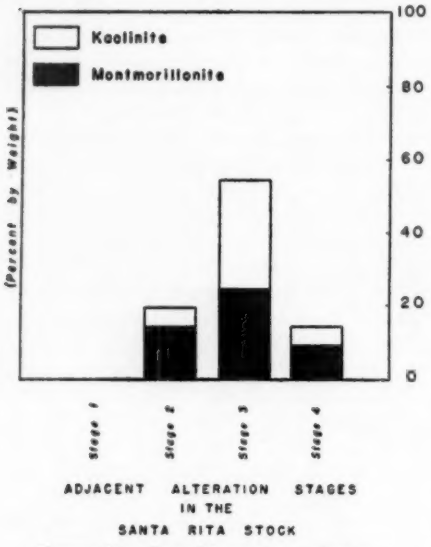

FIGURE 33.—CLAY MINERALS IN ALTERED FELDSPAR PHENOCRYSTS, QUARTZ PORPHYRY DIKE

secondary quartz range up to .3 mm. in diameter, whereas the initial groundmass quartz grains average about .03 mm. Specimens showing silicification of the groundmass are also characterized by a rim of secondary quartz around quartz phenocrysts. The width of the rim is roughly equal to the diameter of secondary quartz grains in the groundmass.

Minor quantities of epidote occur as a secondary mineral in a few dikes. Epidote is a characteristic alteration mineral of rocks affected by zinc-bearing solutions. In general, quartz granodiorite dikes at Hanover followed mineralization, but in a few places sphalerite has been deposited after the emplacement of quartz granodiorite dikes. Epidote may be found, but it is not confined to these rocks; it may be present in post-ore dikes, although always in minor amounts. For example, epidote occurs in a post-ore quartz granodiorite dike near survey station 986 along N338W drift in the Oswaldo mine. Apparently epidotization persisted for a short time after the decline of zinc mineralization. Not all dikes were affected, and the amount of epidote formed is slight, far less than in the hornblende porphyry dikes.

Santa Rita group.—The geological setting of the main dike of the South Pit at Santa Rita has already been discussed. The alteration of this dike resembles the alteration in the quartz porphyry dikes at Hanover. Sericite, muscovite, chlorite, secondary quartz accompanied by a small amount of epidote are common in both localities. However, calcite is prominent at Hanover but absent at Santa Rita, and kaolinite and montmorillonite are abundant in parts of the Santa Rita dike. The absence of calcite at Santa Rita is striking, since the mineral is so abundant at Hanover. However, none was seen in thin section and none was detected by differential thermal analysis. The argillic alteration is reasonably interpreted as superimposed by the alteration attendant with the copper mineralization.

The observation of greatest economic interest at Santa Rita is that the development of kaolinite and montmorillonite in the feldspar phenocrysts is unrelated to the leaching profile but seems directly dependent on the stage of alteration in the adjacent stock. Samples of dike collected from outcrops at various benches from the rim to the floor of the South Pit show by differential thermal analysis curves that the greatest development of kaolinite and montmorillonite (about 50–60 per cent) occurs in the dike feldspar phenocrysts adjacent to Stage 3 of the altered granodiorite porphyry stock. (It has already been noted that feldspar phenocrysts in the stock contain the greatest concentration of clay in Stage 3.) Where the dike is adjacent to Stage 2, the feldspar phenocrysts contain about 20 per cent montmorillonite and kaolinite, while the dike adjacent to Stage 4 contains from 0 to 20 per cent of the combined clay minerals (Fig. 33). The dike was not sampled outside the South Pit where it might be in contact with Stage 1. Presumably the feldspar phenocrysts would show negligible argillic alteration under such conditions. The remainder of the alteration products in the feldspar phenocrysts of the dike are mainly quartz and sericite.

The determinations are plotted on a diagrammatic vertical section in Figure 34. The promi-

nence of kaolinite (Fig. 33) is significant because this mineral accompanies the sericitic alteration of the Santa Rita stock, whereas montmorillonite is the dominant clay mineral in areas of zinc mineralization. Six selected thermal curves from the altered dike specimens show the range in clay mineral concentrations (Fig. 35).

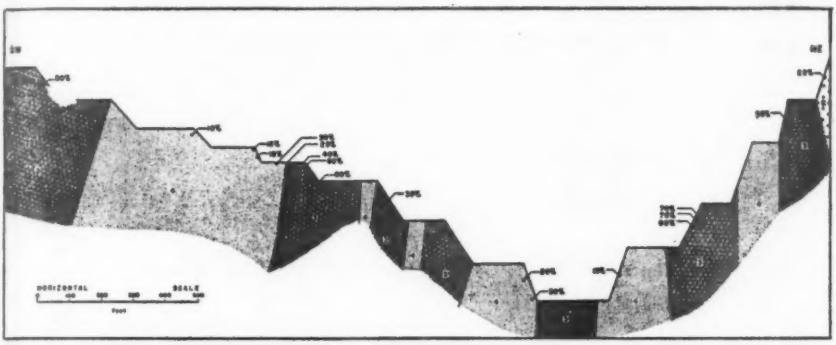

FIGURE 34.—DIAGRAMMATIC VERTICAL SECTION ALONG QUARTZ GRANODIORITE DIKE, SOUTH PIT
Percentages refer to the total clay mineral (montmorillonite plus kaolinite) content of the andesine phenocrysts in the dike. The numbers below the surface refer to the alteration stage of the adjacent stock.

Quartz Diorite Sills in the Colorado Formation

Post-Magmatic alteration.—The Middle and Upper sills of the Colorado formation have been subjected to widespread early hydrothermal alteration in which many of the primary rock-forming minerals have been destroyed. More localized alteration followed. In the early phase, biotite and hornblende phenocrysts are altered to chlorite, epidote, and calcite. Plagioclase is partly replaced by albite, sericite, epidote, calcite, and quartz, and the groundmass is masked by development of similar minerals.

Lasky (1936, p. 56) presents an extended discussion of this feature. He notes in order of development: albite, chlorite, epidote and quartz, calcite, and sericite. Albite is widely developed at the expense of original feldspars, and in places, as in the Upper sill along Whitewater Creek, albite is the only feldspar present. Chlorite replaces ferro-magnesian minerals and forms irregular masses and stringers in the groundmass. Quartz was formed by the liberation of silica during replacement of andesine by epidote. Calcite replaces all earlier minerals except quartz, magnetite, and apatite. Sericite is sparsely distributed through the rock.

This suite of alteration minerals appears in varying proportions throughout the Upper and Middle sills. The intensity of alteration varies from place to place, guided in many instances by local differences in the rock. For example, the highly albitized Upper sill along Whitewater Creek may represent an area of greater permeability. Except for such local variations, the alteration is widely distributed in the sills without regard to fault zones, dikes, or mineralized veins. From this fact Lasky inferred (1936, p. 66) that the sills were altered during the last stages of consolidation by solutions originating within the rock itself. If this interpretation is valid, the albite, epidote, chlorite, calcite alteration is approximately the same age as the sills, and both predate mineralization. Hence there is no correlation between the two events.

Argillic-sericitic alteration.—Besides the alteration impressed on the quartz diorite as a whole, the sills have undergone further hydrothermal attack in places and a bleached rock composed principally of quartz argillic alteration and sericite has been formed, representing a second period of alteration during which a later group of secondary minerals formed at the expense of the original rock-forming minerals and minerals of the earlier alteration suite. Sericite is common to both types of alteration, but plagioclase in rocks affected only by post-

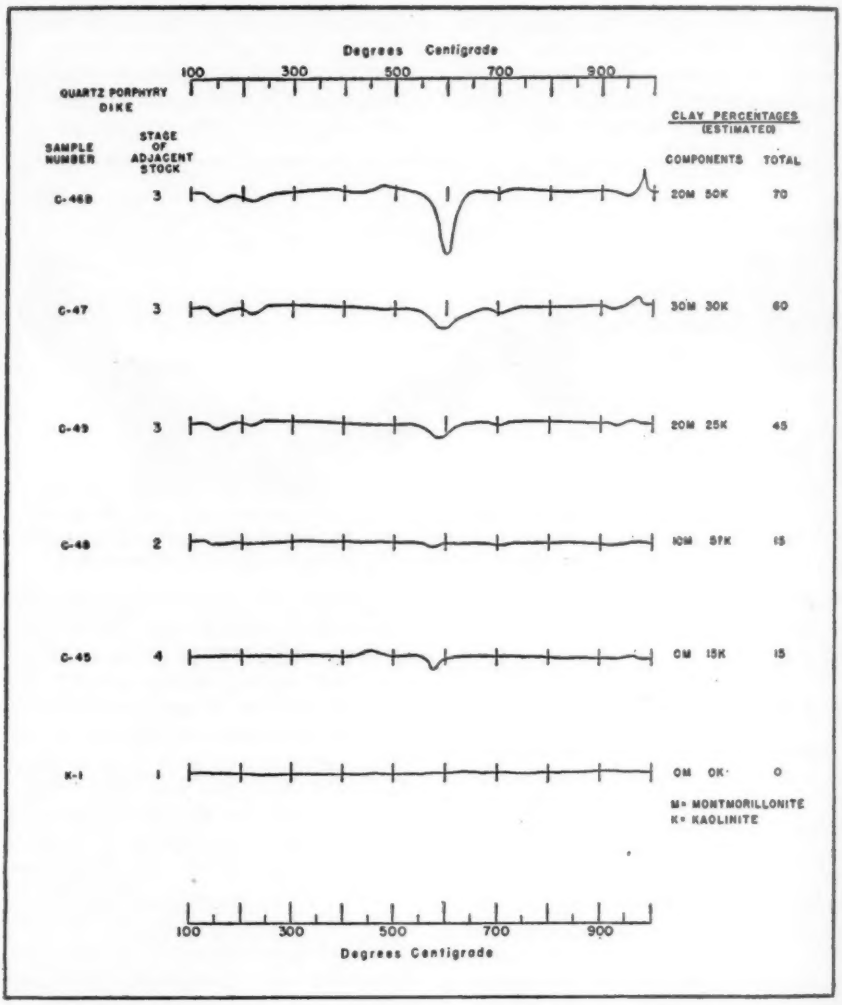

FIGURE 35.—REPRESENTATIVE THERMAL CURVES OF ALTERED DIKE SPECIMENS

magmatic alteration seldom contains more than 30 per cent sericite, whereas plagioclase in rocks affected by the later argillic-sericitic alteration may be almost completely replaced by sericite. Kaolinite and quartz may also be present in the altered feldspars.

Widespread argillic-sericitic alteration occurs in the sills near the Santa Rita stock, but away from the Santa Rita area alteration is confined for the most part to linear fracture zones.

Stages of sill alteration.—Several stages in the intensity of sill alteration were originally defined by megascopic criteria, which could be applied during field mapping; later microscopic examination of selected specimens permits further discrimination. The stages designated B+, B−, C+ and C− (Fig. 36)[4], apply to either the

[4] Stage A, unaltered adjoins B+ but is not shown in Figure 36.

Upper or Middle sill, since the rocks and their alterations are similar.

Stage A[4] shows only the effects of the earlier post-magmatic period of alteration. Phenocrysts of plagioclase, hornblende, and biotite can be recognized in hand specimen. Magnetite may be present. The rock ranges from dark green to buff, due largely to the presence of epidote and chlorite. Microscopic study shows minerals characteristic of the late magmatic alteration. Epidote, chlorite, and calcite are common. The plagioclase phenocrysts are partly replaced by sericite or epidote.

Quartz diorite of Stage B has a bleached appearance, and the rock in surface outcrops is usually streaked and ribbed with brown limonite. The porphyritic igneous texture is preserved by soft white spots, relics of feldspar phenocrysts set in a mosaic of quartz grains. The quartz phenocrysts of the Upper sill remain unchanged. The igneous texture and quartz phenocrysts, where present, help distinguish sill of Stage B from white quartzites of the Colorado formation.

In Stage B, most of the original minerals of Stage A have been destroyed. The feldspar phenocrysts are completely altered to a clay-sericite, and additional alteration is scattered throughout the groundmass. Substantial amounts of kaolinite are developed. Epidote, calcite, magnetite, and chlorite are largely destroyed, although in some specimens chlorite persists in stringers through the groundmass. Limonite lines cavities formed by the removal of magnetite, and irregular brown stains of limonite penetrate the rock. The original quartz phenocrysts remain largely unchanged, although some grains show the addition of secondary silica.

Stage C, the most advanced sill alteration, is marked by partial to complete silicification. The relict feldspar phenocrysts are destroyed except in the least-altered rock. Recrystallization of the quartz matrix is apparent, and grains of in-

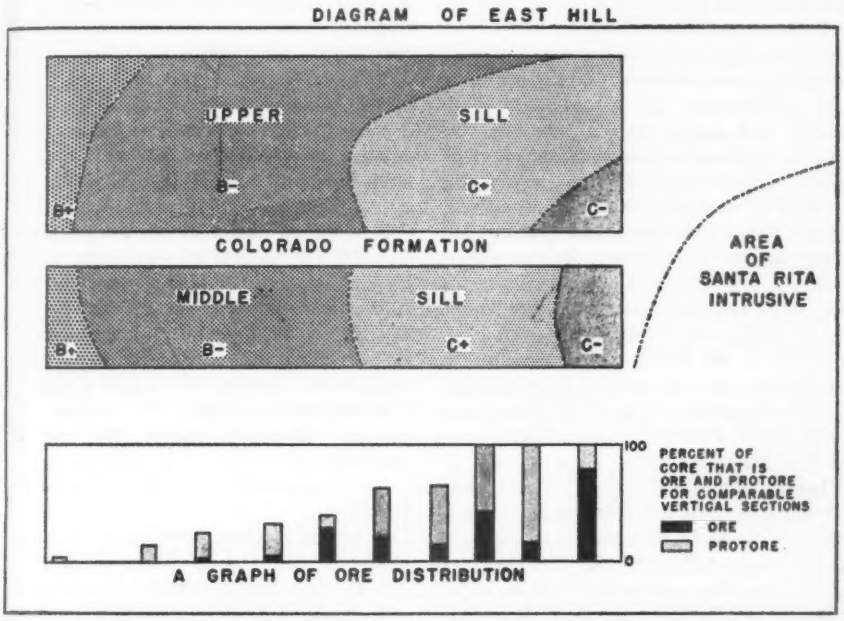

FIGURE 36.—DIAGRAM OF EAST HILL AND A GRAPH OF THE ORE DISTRIBUTION

The letters refer to stages of alteration in the sills. The bars on the graph indicate the relative intensity of mineralization under the surface on east-west lines across the map. The data were derived from east-west rows of drill holes.

troduced quartz are common, distinguished from primary phenocrysts because they are neither doubly terminated nor frosted. Where alteration is most intense, all traces of original igneous texture have been destroyed and the rock almost resembles a quartzite.

Microscopic examination indicates occasional irregular clusters of sericite flakes which represent relict feldspars, but as a rule most of the sericitic and argillic material has been destroyed. Silicification is shown by the recrystallization of the groundmass and the development of rims of secondary silica around original quartz phenocrysts. Interlocking grains of secondary quartz form clusters in the groundmass.

Area West of Santa Rita.—The accompanying map of the area west of the Santa Rita pit (Pl. 11) shows the zones of combined Stage B and C alteration in the Middle and Upper sills. The base geology has been modified from published maps by Spencer and Paige (1935, Plate 1) and Lasky (1936, Plate 1), and unpublished maps by Schmitt and Pollock.

In general, the distribution of argillic-sericitic alteration in the sills is governed by (1) proximity to the Santa Rita stock, and (2) faults and fractures within the sill. The Upper sill along the eastern edge of the map lies within the zone of influence of the Santa Rita stock. Widespread alteration has been produced by hydrothermal activity associated with the Santa Rita intrusive. Advanced alteration characterizes the sills on the eastern edge of the map (Pl. 11), while alteration decreases westward away from the stock.

In the Ivanhoe-Ground Hog area, west of the zone of widespread sill alteration, only Stage B alteration is represented and it is confined largely to linear zones. Most faults cutting the sills are bordered by altered zones. Alteration seems to be equally well developed along both minor fractures and major structures, such as the Ivanhoe-Lovers Lane fault and the Copper Glance fault. The map suggests that Stage B alteration is discontinuous or lacking along certain faults. This may be the result of inadequate exposures, so that discontinuity is probably more apparent than real.

Granodiorite dikes cutting sills may or may not be accompanied by alteration. In the valley across Whitewater Creek from the Kennecott Copper Corporation precipitating plant, the contact between sills and intruding dikes is exposed at a number of places, yet no late alteration can be observed. Alteration is lacking along the easterly of two north-trending dikes immediately north of the Copper Glance fault. In contrast, the parallel dike to the west is bordered by an alteration zone. Many dikes were intruded along fault zones, and some have been re-opened by further movement. Sill alteration adjacent to certain dikes may be a result of later, recurrent fault movement which permitted the rise of hydrothermal solutions.

In mapping, quartz diorite was considered altered if it had a bleached appearance, indicating destruction of the dark minerals. Suites of specimens were collected across altered zones, and 77 thin sections were prepared for study. It was found that destruction of the dark minerals, the criterion used in field recognition of alteration, is accompanied by several other changes. Alteration includes the following processes:

1. Complete removal of epidote, magnetite, and calcite.
2. Almost complete sericitization of plagioclase.
3. Partial or complete destruction of chlorite.
4. Development of limonite.
5. Development of small amounts of kaolinite.

Certain of these changes are effected more readily than others, as seen in Figure 37, based largely upon studies of the Upper sill, which shows a more consistent sequence than the Middle sill.

Calcite is readily destroyed and is lacking in Stage A adjacent to Stage B. Epidote and magnetite persist to the edge of the Stage B zone, but neither mineral was observed within the area of Stage B alteration. The oxidation of magnetite gives rise to limonite. Most chlorite is destroyed near the contact with Stage B, but veinlets of chlorite may persist in the groundmass of advanced Stage C alteration. Quartz phenocrysts remain unchanged. Secondary silica was observed in a few specimens of Stage B, but its occurrence is not consistent. Feldspar phenocrysts become progressively more sericitized toward the Stage B alteration. Even in the least-altered rock the feldspars, except

albite, are clouded with up to 30 per cent sericite as a result of the post-magmatic period of alteration.

Such a sequence near an altered zone is dependent upon the original mineral composition of the rock involved. In the Middle and Upper sills the relative abundance of the components, especially such secondary minerals as epidote, chlorite, calcite, and sericite, varies considerably. Epidote is very irregular in distribution. Where abundant the epidote partly replaces feldspar, and little sericite of the post-magmatic alteration is developed.

The altered rock of Stage B is composed essentially of quartz, sericite, and stains of limonite. No clay minerals were identified in thin section, but of five representative specimens checked by differential thermal analysis four gave an indication of kaolinite and a possible trace (less than 5 per cent) of montmorillonite. For the crushed rock as a whole, the following figures were obtained:

Specimen 39	10% kaolinite
27	5
50	5
6	1
29	nil
Average	4%

It is difficult from surface studies west of the Santa Rita pit to date the sill alteration or to determine its relation to mineralization. There seems to be no correlation between intensity of argillic and sericitic alteration and zinc ore-bearing structures. Faults along which ore bodies have been exploited are accompanied by no greater argillic alteration than structures along which prospecting has been a failure.

A clue as to the age of alteration is furnished in the area just northwest of the Santa Fe railway depot. Here alteration has taken place along faults which cut and displace a dike of hornblende porphyry, which suggests that alteration followed emplacement and deformation of the dike. If alternatively, alteration was developed along a fracture, the dike was emplaced and deformed by a later movement along the original structure. The faults have easterly strikes, discordant with the main structural lines along which recurrent movement has taken place. Thus, they seem to be minor structures, probably with a simple history. This inference supports the interpretation that both the faults and the sill alteration are later than the hornblende porphyry dike.

Alteration and mineralization on the East Hill.—The term "East Hill" refers to the area adjacent to the east side of the South Pit bounded on the north by the highway, and on the south by Niagara Gulch.

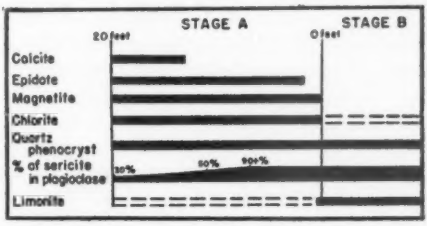

FIGURE 37.—CHANGE IN MINERAL CONTENT OF SILL AT CONTACT BETWEEN STAGE A AND STAGE B ALTERATION

The area affords an excellent site for studying rock alteration accompanying the copper mineralization in the sills where the sills and sedimentary rocks have been invaded by offshoots from the stock. Surface geology and coordinate diamond drill cores furnish a three-dimensional picture of the alteration and the correlation of alteration with mineralization.

The sills and sedimentary rocks are inclined away from the Pit (Fig. 2). Figure 38, a generalized E-W cross section through the East Hill, shows the general eastward dip of the beds, the usual conformability of the sills to the sedimentary rocks, and the cross-cutting nature of the granodiorite porphyry intrusive. East of Santa Rita the sedimentary rocks form a synclinal trough. Along the east limb of this syncline, the older formations outcrop in sequence along the highway running eastward from Santa Rita. Faulting occurs on a minor scale, although jointing and fracturing are widespread, particularly in the Colorado formation.

Earlier hydrothermal alteration is indicated by replacement and disappearance of particular minerals independent of weathering and leaching. The final phase of this alteration is extensive silicification regardless of the initial character of the rock, whether sill, sedimentary rock, or granodiorite.

Supergene leaching is indicated at the surface and in the upper parts of drill holes throughout the area. At the surface numerous empty cubic cavities reveal the previous existence of pyrite crystals that have been removed. Immediately below the surface these cavities are filled with limonite. Pyrite, chalcocite replacing pyrite, and chalcocite masses are present at depth. In the zone of most intense hydrothermal alteration, the pyrite seems to have been destroyed by hydrothermal solutions which so altered the rock that primary pyrite was removed and the cubic casts disintegrated. In the leached zone tetragonal disphenoidal casts which would indicate primary chalcopyrite, were not observed. Leaching removes copper mineralization at the surface. To correlate the alteration due to hydrothermal activity with ore deposition, the extent of supergene leaching must be ascertained. This may be accomplished in two ways. First, the lower limit of intensive leaching may be set at the level where unoxidized pyrite initially appears. Above this level the rocks are deficient in copper values. Second, comparatively fresh biotite granodiorite porphyry occurs at the surface in the North Pit and toward the Kneeling Nun to the southeast of the South Pit. Here the supergene effects on the feldspars and the dark minerals are slight.

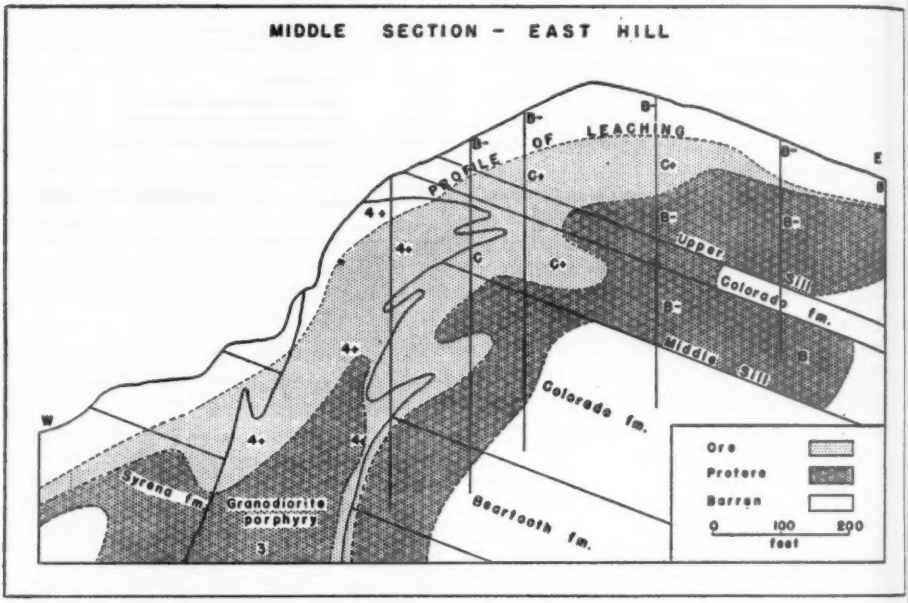

FIGURE 38.—CROSS SECTION OF MIDDLE PORTION, EAST HILL

Cores from some 30 drill holes show that the profile of leaching is essentially constant across the East Hill, even in the zone of strongest alteration.

On the East Hill, the Middle and Upper sills are intercalated between layers of the Colorado formation and lie above a lobe of the intrusive stock which tapers out to the north. The sills are inclined eastward at about 15°. Because of this comparatively moderate inclination, both the Middle and Upper sills are well distributed at the surface. The uniform petrology and susceptibility to alteration are also advantageous. At Santa Rita Stage C is best shown on East Hill. In surface specimens and particularly in the unweathered cores, it is possible to distinguish the less intense part of an alteration stage from the more intense part. C+ indicates that part of Stage C in which frayed feldspar relicts may still be distinguished in hand speci-

men; C− indicates a rock that looks completely silicified. This distinction is neither sharp nor important theoretically, but it provides sufficient subdivision to show the zoning of the alteration.

Surface samples of the Upper and Middle sills were collected systematically and catalogued according to the above classification. Likewise representative lengths of diamond drill cores were sampled. Thin sections of all these samples were prepared and studied to provide the data used in deriving the subsequent diagrams.

A direct increase in intensity of alteration occurs southward toward a lobe of the granodiorite intrusion (Pl. 1). It is believed that the contact between the alteration stages swings around to the south on approaching the granodiorite lobe because the lobe does not extend very far to the east. About 1500 feet east of the highly altered area of the sills, an outcrop of the Upper sill has been identified as Stage A and there is no evidence of mineralization.

In the relative intensity of mineralization estimated from drill hole assays for particular vertical sections of the East Hills (Fig. 36) a close correlation between sill alteration, proximity to the stock, and ore values is evident.

The sills are not sufficiently thick to yield great changes in alteration with depth. Figure 38 shows the horizontal effects of alteration due to proximity to the granodiorite intrusive apophyses.

The alteration stages in the granodiorite intrusive in the East Hill are the same as described for the stock. Stage 1 rock, however, does not occur either in the drill cores or on the surface. In addition, Stage 4 has been subdivided into 4+ and 4−. Stage 4− refers to the most intense phase of alteration of the granodiorite in which the rock is essentially quartzite. In 4+, ragged feldspar outlines are still observable.

The most intense alteration in the granodiorite intrusive has occurred near the contact of the stock with the sedimentary rocks. At the south end of the East Hill, Stage 4− occurs at the surface but Stage 2 outcrops only a few hundred feet farther south. No drill hole went deep enough to determine whether Stage 1 would be reached at depth in the "heart" of the stock or whether another increase in alteration occurs. Exposures south of this section reveal only more Stage 2 intrusive to the contact of the granodiorite with its latite cover.

The diagrams referred to in this section are based on data from detailed surface mapping, 30 drill holes and the East-West tunnel which penetrates the East Hill. The cross sections are typical and the relationships indicated were verified from a dozen other sections taken along convenient east-east or north-south lines.

Figure 39 indicates that below the profile of leaching, the mineralization follows the periphery of the stock and that it enters the country rock from the fingers of the intrusive. Also it is evident that within 400 feet the alteration stage increases from 2 to 4, the ore values increasing correspondingly. Drill cores in this section show a few spots of Stage 4−, but they are not extensive enough to be mapped. These are also seen in certain locations in the East-West tunnel. The ore values are always small in granodiorite of Stage 4−. This is consistent with observations in the pit. However, in the pit the stage most productive of ore is 3, and these sections indicate that at the contact between the country rock and an outer lobe of the stock, the largest concentration of ore occurs in the least-altered part of Stage 4. This may be a local and more or less apical feature indicating a greater concentration of the rock-altering ingredients, a slightly higher temperature before mineralization, or a different timing in the introduction of the copper mineals.

The east-west section (Fig. 38) shows the correlation of alteration with mineralization. The regular profile of leaching is superimposed over the section effecting a concentration of the ore values at the base of this weathered zone (Fig. 39).

The following observations appear from the diagrams.

1. The sills are more favorable for mineralization than the beds of Colorado formation.
2. The most intense mineralization in this area occurs around the edge of the stock and extends out into the country rock a short distance.
3. The ore is more closely associated with the fingers of the stock than with the main body under the East Hill.

Observations (2) and (3) support the hypothesis that the ore-bearing solutions passed

around the periphery of the rock. These sections through the East Hill shed light on the problem of ore genesis. Figures 38 and 39 show the close relationship of the ore with the tip of the intrusive rather than the leaching profile. ions from some deposit (chalcopyrite) far above in the stratigraphic column which has been entirely removed by erosion. The present distribution would then be due to the porosity and pyrite content of the stock periphery.

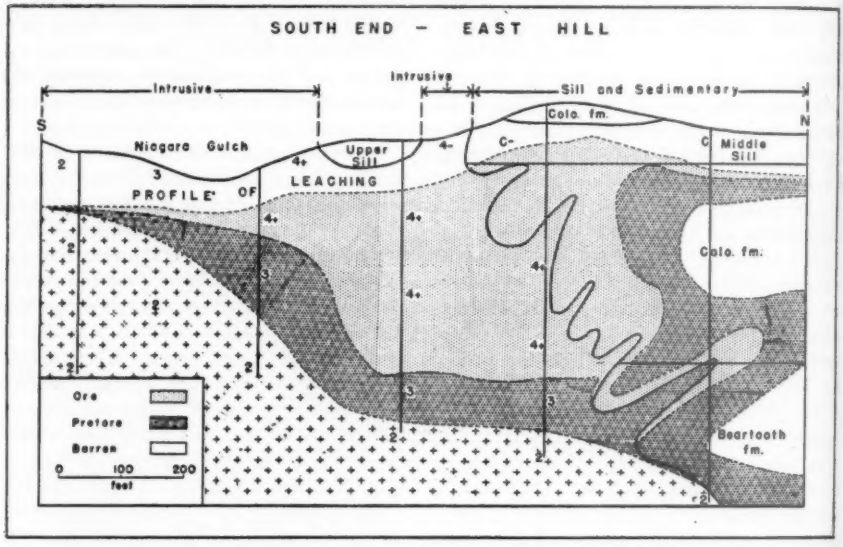

FIGURE 39.—CROSS SECTION OF SOUTH END, EAST HILL

Figure 39 shows the striking unconformity between the profile of leaching and the ore deposition. Mineralization follows the stock outline and the alteration pattern rather than the leaching profile.

Figure 39 shows a typical sequence found in drill holes that have cut through granodiorite fingers into sedimentary rocks and at greater depth have transected more granodiorite. In each case, ore value has increased immediately adjacent to the stock. This diagram emphasizes how closely the lower boundaries of the ore zones coincide with rock alteration.

The evidence may be interpreted in harmony with the alternative theories of ore genesis at Santa Rita. If the ore is a result of high, temperature replacement of pyrite by chalcocite modified by some secondary sulfide enrichment, it is somewhat unique. Nevertheless, this a reasonable interpretation on the data available. On the other hand, such a distribution of ore could be a result of supergene waters carrying copper

Epidote alteration in the Ground Hog Mine.—In order to relate the surface sill alteration with zinc mineralization, suites of specimens were collected in the Ground Hog mine from sills near the Ground Hog fault and the Ground Hog ore body. The Ground Hog fault is a major pre-ore structure which apparently guided mineralization. Two suites of Middle sill specimens were taken from diamond drill holes which penetrate the fault. A third group was collected from the Upper sill in the footwall of the Ground Hog vein at the 600-22 winze pocket. From these specimens 16 thin sections were prepared for study.

An increase in silica toward the fault was noted in all three suites. Epidote is common throughout, and in the specimens near the Ground Hog vein epidote increases toward the fault. Calcite shows a corresponding decrease. In the other suites calcite and epidote occur throughout. No specimens showed destruction of epidote, which is the rule in surface sill alter-

ation. Chlorite is present throughout. Pyrite increases toward the fault, and magnetite, where present, is also more abundant near the fault.

There is a marked contrast between sill alteration near zinc-bearing structures at the Ground Hog mine and the sericitic alteration that is common at the surface. Sericitic alteration is characterized by destruction of epidote, chlorite, calcite, and magnetite. On the other hand, sill alteration near zinc ore bodies is characterized by the stability of epidote, chlorite, calcite, and magnetite. This alteration at the Ground Hog mine is similar to epidote alteration of pre-ore dikes at Hanover.

Significance of Dike and Sill Alteration

Types of alteration.—Three types of dike and sill alteration have been described in previous sections: (1) epidote-chlorite-albite alteration widely developed throughout the sills as a whole, (2) epidote alteration in dikes and sills which were attacked by hydrothermal solutions associated with zinc mineralization, (3) argillic alteration of the sills by solutions accompanying copper mineralization. The three types are believed to represent different periods of hydrothermal activity although some rocks have been affected by all three.

Post-Magmatic sill alteration.—The earliest alteration was imposed upon the Upper and Lower sills as a whole. Rock-forming minerals were replaced by epidote, chlorite, calcite, albite, and minor sericite. No unaltered ferromagnesian minerals were seen in the specimens studied. The alteration is so universal and the secondary minerals are so intimately disseminated throughout the quartz diorite that the altering solutions must have come from within the magma itself. This alteration is approximately the same age as the sills, and both predate mineralization, therefore the post-magmatic alteration of the sills is not related to later mineralization.

Epidote alteration associated with zinc mineralization.—Pre-ore dikes and sills in the Hanover and Ground Hog areas have been altered by hydrothermal activity connected with zinc-bearing solutions. In many cases the dikes served as conduits for the solutions, and ore bodies were formed by replacement of adjacent limestones. In a few places sphalerite was deposited within an altered dike.

The minerals formed by this type of alteration are epidote, chlorite, and calcite. Of these, epidote is the most abundant and most striking in hand specimen. Epidote occurs in the igneous rocks and argillaceous sedimentary rocks (Pl. 9) at all places where there is evidence of zinc mineralization. Certain post-ore dikes in the Hanover mine contain sparse epidote, showing that epidotization slightly overlapped the period of zinc mineralization.

In view of the close relation between epidote and zinc mineralization, it is well to bear in mind that epidote has not been observed at the surface level of the Santa Rita stock, except for a few grains seen in thin sections of the quartz porphyry dikes. Certain cores, however, suggest the possibility of conditions more nearly comparable to Hanover at depth.

Argillic Alteration Associated with Copper Mineralization.—West of Santa Rita linear zones of argillic alteration of moderate intensity are found within the upper sill. At few points is the intensity comparable to that in altered sills east of South Pit where copper was deposited. These zones of alteration follow fractures within the sill and occur along structures several of which are known to carry zinc ore at depth. Near such ore bodies both dikes and sills are epidotized. But this alteration may be obliterated by later argillic alteration. Under this interpretation, the zones of sill alteration (Pl. 11) indicate fracture zones in the sills. Certain fractures may have guided zinc-bearing solutions, but the argillic alteration was not produced by these solutions.

Post-ore quartz granodiorite porphyry dikes at Hanover are altered by clays, calcite, and chlorite. The alteration is similar to alteration in the sills, although the suite of secondary minerals is not identical. The alteration which followed zinc mineralization may be connected with hydrothermal activity accompanying copper mineralization. However, the suite of alteration minerals is not identical, and such a correlation is indefinite. Still, alteration in the quartz granodiorite dikes at Hanover most nearly resembles argillic alteration at Santa Rita.

Areas of Mineralization

The correlation of argillic alteration with the ore zone of the South Pit at Santa Rita raises the question as to how far the results of the present study may be applied in the search for ore. There are limitations which must be emphasized. It should be remembered that the location of contacts between the various stages of alteration is approximate and not precise.

However, the occurrence of the argillic stage in the alteration sequence furnishes a general indication of the trend of the ore body. This may be applied where surface exposures are available or where the alteration stages have been encountered in drilling. The delineation of ore zones has not been attempted in this study; the next step might well be the development of such a map by continuing the detailed studies already started.

Mapping of the alteration stages also provides negative information which is important. The stages that are non-ore-bearing or appear to contain minor amounts of ore are separated from the productive stage.

Areas of copper mineralization have not been confined to the altered zone of the biotite granodiorite porphyry, but have extended into the bordering sills and sedimentary rocks. The migration of the ore-bearing solutions, however, has not been great and in most instances there is reason to believe that the impregnated sedimentary rocks are marginal to the mineralized phase of the porphyry.

Two contrasting theories of ore genesis appear reasonable in terms of the evidence available. Two others have been ruled out as unlikely. The determination of the correct theory would be of considerable practical interest.

The extent to which the formation of ore has been dependent upon the supergene or the hypogene process has not been determined. It has been generally assumed that the ore body gradually disappears at a certain depth and consequently, from the practical standpoint at least, the control of the ore body is supergene. On the other hand, the concept of a marginal argillic zone lying along the flanks of the intrusive is worthy of careful consideration from the standpoint of exploration by drilling.

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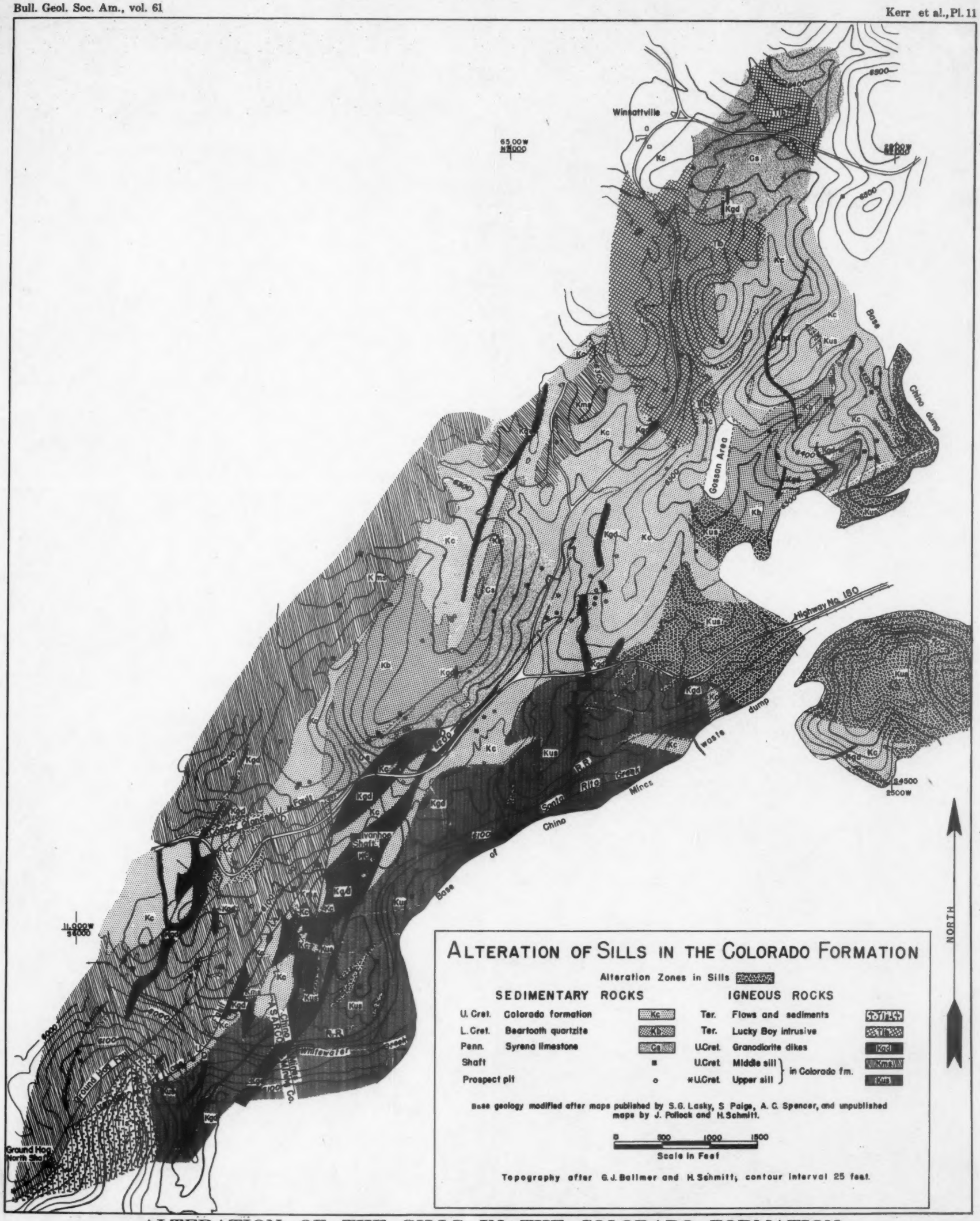

ALTERATION OF THE SILLS IN THE COLORADO FORMATION

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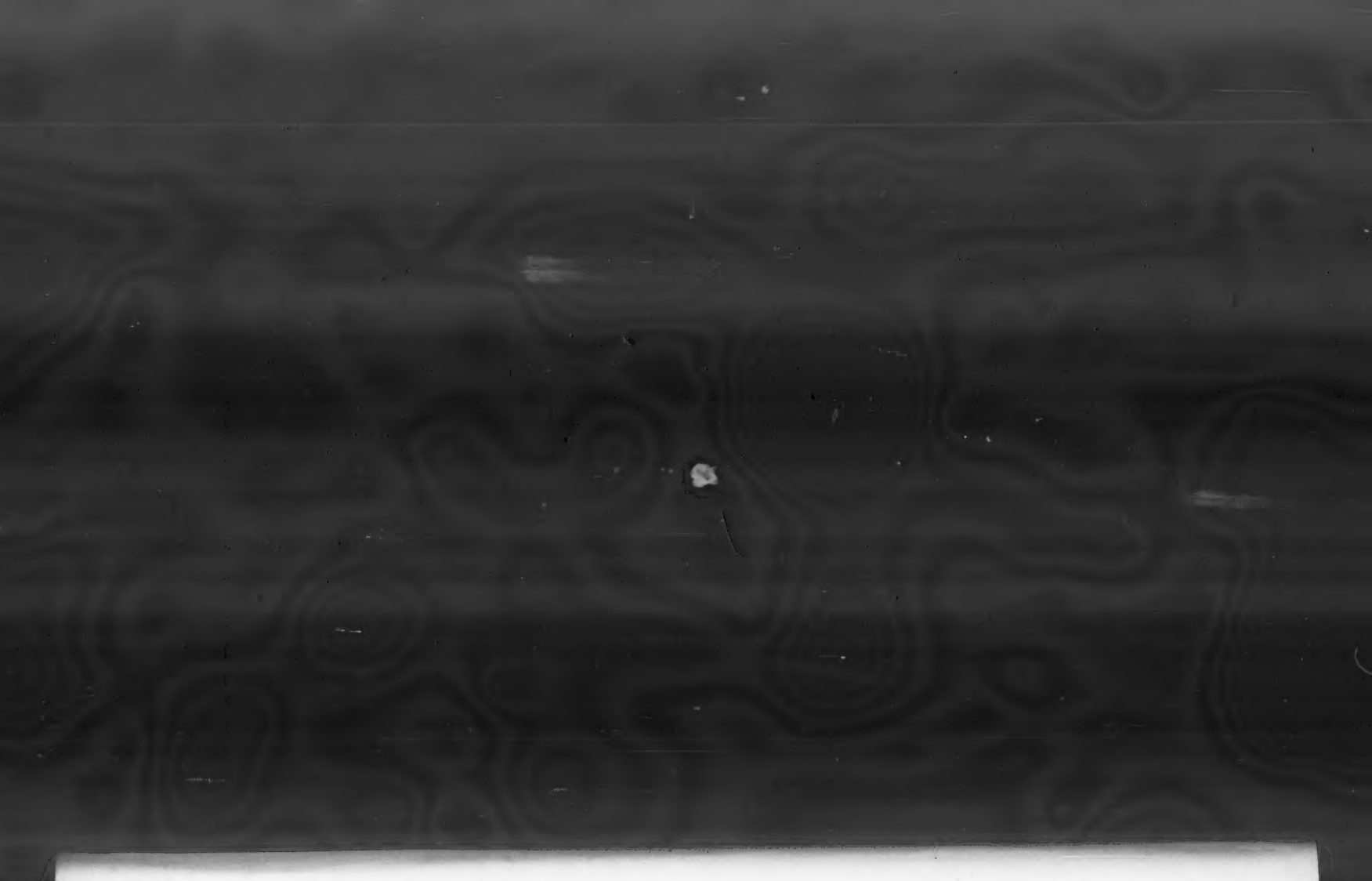

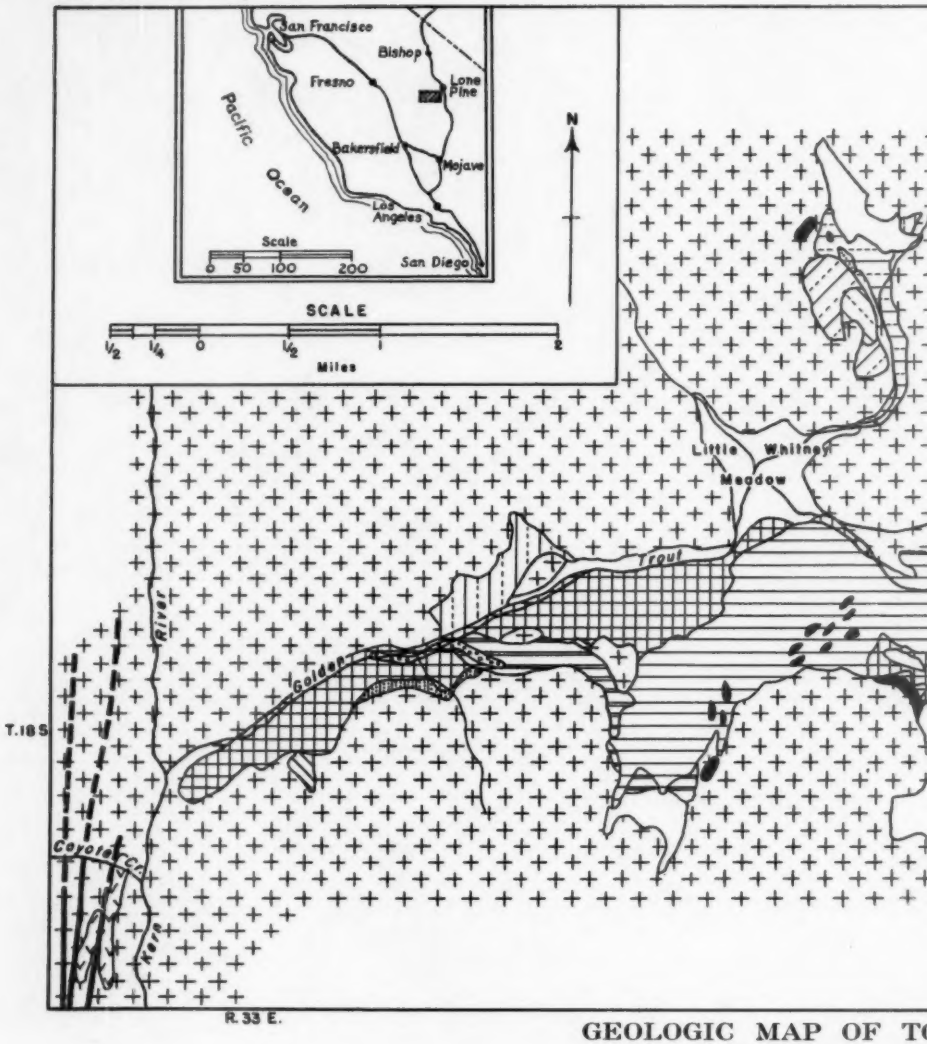

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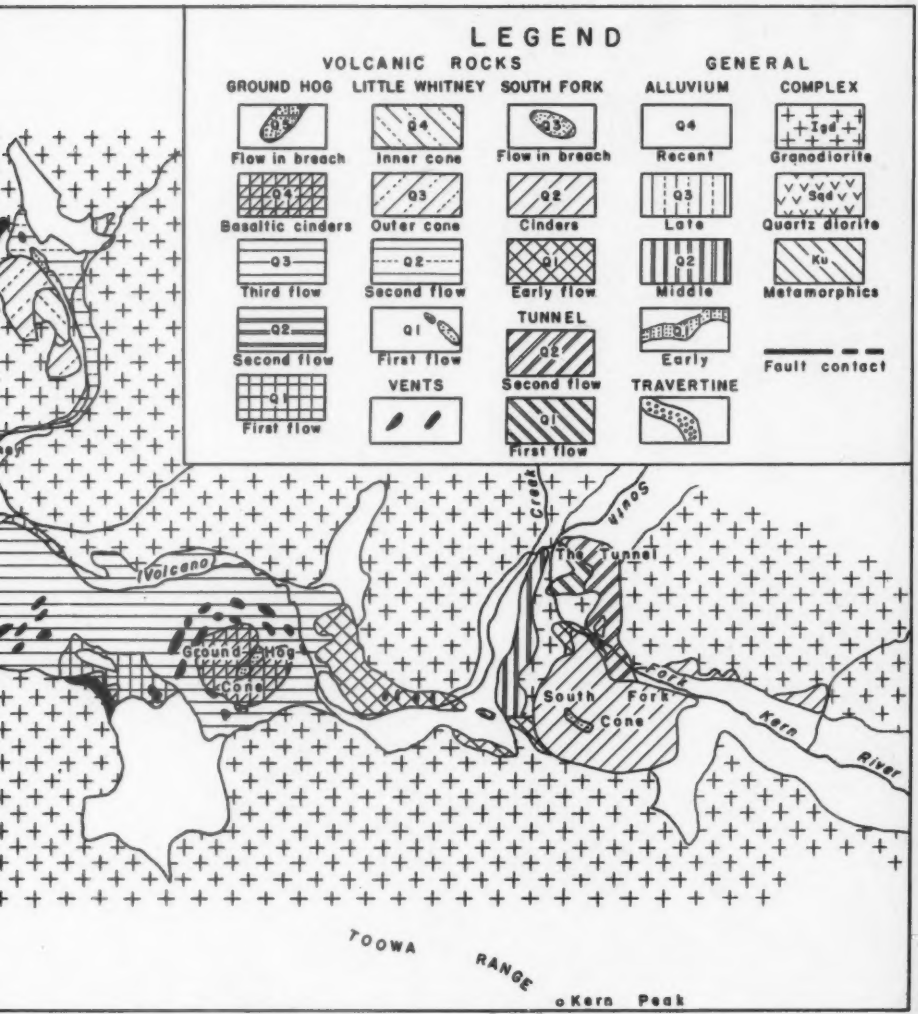

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VOLCANIC GEOLOGY OF TOOWA VALLEY, SOUTHERN SIERRA NEVADA, CALIFORNIA

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Abstract

Toowa Valley, a broad east-west late mature valley astride the Sierra Nevada west of Olancha, California, contains flows and cones composed of olivine basalts, scorias and agglomerates in a volcanic field 4½ miles long, including 4 eruptive centers, one of which is hitherto unreported. Each center shows several flow phases followed by cone building, breaching, and later partial reconstruction. Volcanic domes in and near Toowa Valley are also described. Contact relations of flows of Toowa volcanism, swamp sediments of meadows of prevolcanic origin, volcanic domes of an adjacent area, and recognized physiographic surfaces of the Sierra Nevada, allow relative age determinations of several heretofore undated events.

Introduction

Geologic studies in the Kernville, Olancha, and Mount Whitney quadrangles, southern Sierra Nevada of California, have been pursued since 1932, and have resulted in the publication of two general studies (Miller and Webb, 1940; Webb, 1946) and several papers on special problems (Webb, 1936; 1938; 1941). This paper discusses cones, domes, and flows in and adjacent to Toowa Valley in the Olancha quadrangle, volcanics briefly described by Lawson (1904, p. 319–32) and Knopf (1918, p. 73). The number, sequence, relations, and character of volcanic episodes have been investigated, and suggestions are advanced regarding relative age of volcanism and geomorphic events.

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Geographic Aspects

Toowa Valley, named by Lawson (1904) from the Toowa Range which parallels the valley on the south, is a high-level east-west valley, part of which is drained westward by Golden Trout Creek (also known as Volcano or Little Whitney Creek), and part eastward by South Fork of the Kern River. Volcanic features are (1) flows and cones along Golden Trout Creek, (2) cones and flows north of Little Whitney (or Long) Meadow, and (3) cones and volcanic domes (Knopf, 1918) on South Fork of the Kern (Pl. 1).

Toowa Valley is broad and open, about 8600 feet high, slightly less to the west, with cones 400–600 feet above the present valley floor. Sparse vegetation on volcanic rocks and drainage stagnation against cones and flows suggest recency of volcanic activity. The cones are built on the surfaces of lava flows or on deeply weathered quartz monzonite. Two prominent volcanic cones lie on the axis of the valley, one astride the South Fork-Golden Trout Creek divide (henceforth referred to as South Fork Center), and a second here named Groundhog Center in the valley 2½ miles west of the first. Other vents are across South Fork opposite South Fork Cone (named Tunnel Volcanic Center), and Little Whitney Meadows Center on Little Whitney Creek 2 miles northwest of Groundhog.

A complex series of stream captures has affected Golden Trout Creek and South Fork of the Kern River. In Toowa Valley the slight gradients of the two master streams slope currently to the Kern River directly for Golden Trout Creek and indirectly after 75 miles of flow, also to the Kern River for South Fork of Kern River (Fig. 1). Drainage has been reversed at least twice in the physiographic history of Toowa Valley causing the headwaters of Golden Trout Creek to feed across Tunnel Divide into South Fork, and conversely, the headwaters of South Fork to feed Golden Trout Creek across the same divide. Slight shifts in drainage balance, occasioned sometimes by volcanism, caused captures (Webb, 1946, p. 377–380).

Geology of the Toowa Volcanic Field

General Character of the Volcanic Rocks

Olivine basalts and basaltic agglomerates occur in mappable units, separable primarily on textural and structural differences, and by their field relations. Varieties noted are massive olivine basalts, basaltic scorias, banded red basalts, clinkery basaltic *aa*, cinders, and agglomerates.

Tunnel Volcanic Center

Three phases of eruption are evident. (1) Cinders, concentrated northwest and south of the vent, showered on a low ridge of quartz monzonite, constructing a small cone base about 50 feet high. (2) Concurrently, a highly vesicular, pumiceous, olivine basalt, carrying subangular granules of quartz, welled up and slowly cascaded over the low cinder cone rim and rapidly congealed. Olivine coronas surround the quartz, suggesting late incorporation of the quartz (Webb, 1941). (3) Finally, olivine basalt rose from the central vent astride the quartz monzonite ridge and slowly flowed down north and south slopes forming layers 6–10 feet thick. The flow surface is grooved, creased, and furrowed, with an upper breadcrust surface. High viscosity at time of eruption is suggested by (1) large inclusions of spheroidally weathered boulders of quartz monzonite gathered during surface flow around which wrap ropy basalt; (2) absence of baking effects or partially oxidized shells about the included xenoliths; (3) the short distance (¼ mile) of

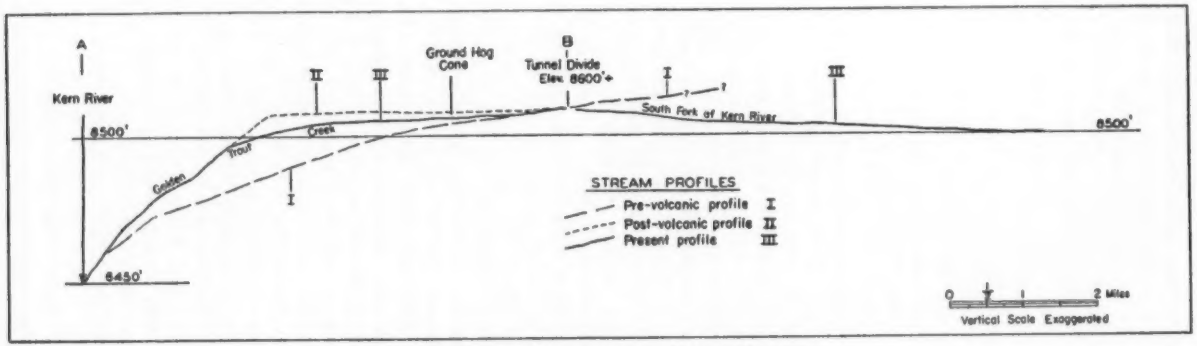

FIGURE 1.—STREAM PROFILES FROM TOOWA VALLEY
Inferred reconstructions of early and late stages of valley evolution.

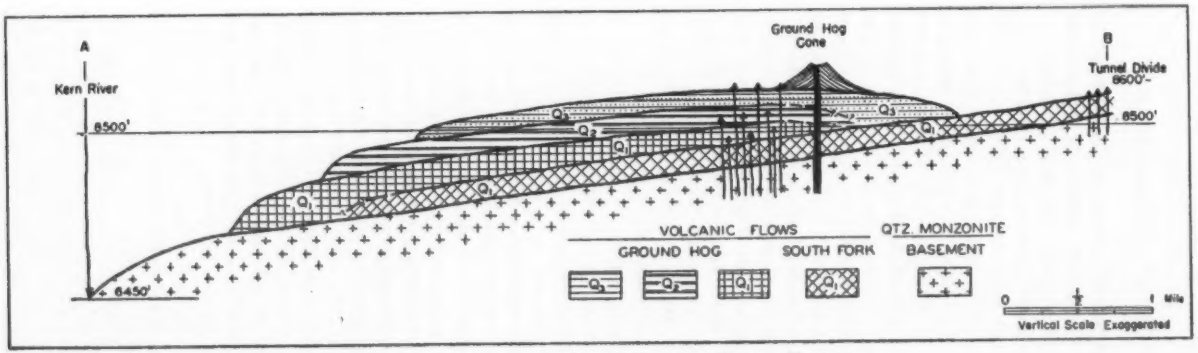

FIGURE 2.—DIAGRAMATIC CROSS-SECTION OF TOOWA VALLEY
Showing inferred relations of Ground Hog and South Fork flows. Arrows suggest centers of eruption, although all vents are presumed to originate from a single magma source. Vents may converge at depth. Thickness of volcanic rocks exaggerated.

flow from the vent source under especially favorable flow gradients.

South Fork Volcanic Center

Three volcanic phases are represented. (1) Flows of vesicular basalt, 6–10 feet thick, weathered to brick red, may be traced from the west and southwest base of South Fork cone, west along Golden Trout Creek until they disappear under overlapping lavas from Groundhog Center. The vents contributing the magma for this phase were not found; however, the flow is pierced down-valley by several vents which added basalt to the still active flow. Flow layering dips into such vents. Inclusions of quartz monzonite are common especially close to vents. (2) A cinder eruption produced breccias and agglomerates, with glassy groundmass, which compose the bulk of South Fork Cone. Built on a bedrock ridge that descends northward into present Toowa Valley, the cone summit is 600 feet above the present stream and basement complex on the north side, but only 400 feet from bedrock on the south side. (3) In a final phase, a central plug of basaltic scoria developed on the south and west rim of the cone.

On the north canyon wall of South Fork of the Kern and easterly from South Fork cone, cinders extend up hillslopes, with feather edges away from the cone itself. Sorting of cinders, with coarsest fragments nearest the cone source, may be explained by generally prevailing west-southwest wind at the time of eruption, blowing cinders to the east and northeast. Smaller scale cinder concentration, found near Tunnel Volcanic center, show similar space relations.

South Fork cone is breached to the north by a slight, but distinct break, but no later volcanic activity has occurred.

Groundhog Volcanic Center

First phase.—First, highly fluid basaltic magma, discharged from centers near the present west base of Groundhog cone, flowed west, hugged the north side of the valley of Golden Trout Creek, and displaced the stream. The vent sources of this lava cannot be identified with certainty since their loci are covered by later eruptions. Flow continued westward about 4 miles down Golden Trout Creek canyon, to within an eighth of a mile of the Kern River. A gorge 800 feet deep at the junction with Kern Canyon was filled almost completely by flows from this eruption. Golden Trout Creek has since exposed lavas and bedrock in cutting a new gorge 100–300 feet deep on the north edge of the older valley, exposing a representative section of basalts. The stream plunges then over a 100-foot fall (at the basalt-quartz monzonite contact) and flows into Kern River (Fig. 1). Immediately upstream from the falls, 12 flows with interbedded agglomerates, nearly 300 feet thick, are exposed. In another section, 14 distinct flows are piled in 225 feet. Flows dip downstream at an average angle of 7°, although locally much steeper dips are measured. No soil layers were seen and oxidation is only occasionally marked by red zones about half an inch thick. Though it was impossible to trace specific flows upstream any distance, many of the thin flows may be interfingering members of the same volcanic sheet, since the pre-lava valley was irregular and the lava stream may have been braided. All these basalts show columnar jointing; some on the north wall of the gorge show nearly horizontal jointing, developed normal to the canyon wall.

Second phase.—The second discharge from Groundhog Center erupted highly vesicular dark-reddish basalts, emanating presumably from fissures, on the south side of Toowa Valley, since these lavas flowed westward on the south side, spilling into low meadowlands now bearing tributaries to Golden Trout Creek. Such flows moved west for nearly 4 miles. In lower reaches, these flows overlapped those of the first eruption from Groundhog Center, and were superimposed upon them (Pl. 1). These flows are less extensive than the first because they are largely covered by later lavas. During this phase, large sheets of travertine and calcareous tufa were deposited by accompanying hot waters; these today form the arch of a small natural bridge which is found in western Toowa Valley.

Third phase.—The third eruption from Groundhog center extruded black basaltic *aa* (in contrast to redder second-phase flows) over nearly 3 square miles of Toowa Valley. This recent eruption came from a series of well-

defined vents circularly arranged about the Groundhog cinder cone. Vents are as large as 25 feet long, and 6–8 feet wide, with final eruptions often developing small volcanic domes over the vent centers. In all cases vent fissures are marked by pressure ridges and gas blowouts in the *aa*. The domal extrusions over vent fissures may occasionally be seen in cross-section, where flow structures are mappable.

The forward edge of the flows of the third eruptive phase is a low escarpment from 6 to 25 feet in height along a front of nearly 7 miles; the scarp reaches its greatest height on the northern edge where the flows piled against spurs which enter Toowa Valley from the north. The forward edge is blocky and broken, blocks 3–4 feet across being common. To the west the escarpment decreases, and the latest flows of this stage then spread into the embayment created by the mouth of Long Creek at Little Whitney Meadow, and to the south, where a north-flowing graded tributary joins Golden Trout Creek. Here the escarpment seldom exceeds 6 feet high. On the south and west margins of the Toowa field, the latest flows have in part completely overridden the flows of the second phase, in places having sent tongues across the older flows to spread out in front of an older and barely perceptible (second phase) escarpment. These tongues of *aa* now form ramps up which the escarpment of second and third phase flows may be ascended.

Most of the flows of the third phase spread westward down the prevailing slope but, as the fissure eruptions of the third phase occurred, a central shield of lava, somewhat thicker than its marginal counterpart, must have formed on the site of the Groundhog cinder cone, forming its foundation. Some of the flows of the third volcanic phase edged eastward against the prevailing gentle slope of Toowa Valley for a distance of about a fourth of a mile and north a similar distance, overlapping the earlier flows from the South Fork volcanic center. A few lava streams moved northerly into south-draining tributaries of Toowa Valley, in some instances completely blocking them. The *aa* flows of the third volcanic phase vary from 1 to 25 feet thick, depending upon proximity to vent source.

Fourth phase.—The fourth phase of volcanic activity from the Groundhog Center developed the Groundhog cone. Rising 800 feet above the general level of the volcanic field, the cone is built on a ridge of quartz monzonite that extends north from the south side of Toowa Valley. The extent of the foundation ridge is indicated by bedrock protruding through the *aa* flows of the third phase, and through the cinder cone itself to within 300 feet of the summit, on the south and west side of the cone (Pl. 2, fig. 1). The cone is composed of well-bedded agglomerates, containing scoria, ash, cinders, and bombs of varying sizes. Occasionally flow units are intercalated in the lower part of the cone; the higher layers are more completely agglomeratic. Spindle bombs 6 feet long are embedded in the agglomerates, along with blocks of scoria of comparable size.

The 350-foot breach on the north side of the cone shows clearly the structure of the agglomerates. They dip outward from the cone center with basal beds dipping as low as 6° radially; the present topmost layer dips from the west rim west at 32° maximum. Twenty-nine-degree dips were recorded in other parts of the rim agglomerate. The slope of the agglomerate layers suggests, when projected, that the Groundhog cone was formerly 150–200 feet higher than the present breached cone, the summit lying closer to the western than the eastern rim of the present cone. Inward slumping of large blocks of agglomerate and the slightly deformed in-dipping edges of the beds just inside the crater rim suggest strongly that partial collapse of the cone occurred after it was completed.

Field relations indicate that Groundhog cone is built upon, and is entirely younger than, third-phase lavas. The deformed beds of the crater rim and the slumped agglomerate blocks may indicate, however, that late in the cone building, magma erupted from vents at the north base of the cone and rafted some of the cone material away, causing the breaching.

Final phase.—The final phase of Groundhog Center produced a single flow of massive olivine basalt, originating within the crater and pouring out to the north through the breach, flowing about 75 yards before it congealed. Paralleling this flow on the east is a fissure ridge from which much lava of the third phase was ejected; how-

ever, these bear no apparent direct genetic relation.

Little Whitney Volcanic Center

General.—Northwest of Groundhog Cone, in the valley of a tributary joining Golden Trout Creek at Little Whitney Meadow, a volcanic sequence has produced topographic disruptions, and, as in the Groundhog center, consists of five eruptive phases. However, no products of this volcanic center are in contact with any products of the other volcanic centers.

First phase.—The first phase developed a small massive basaltic lava flow about 20 feet thick, which emanated from fissures lying northeast of the present cinder cone. This flow is short, extending only 250–300 yards from the vent, but with enough volume to displace a small stream to the east. The previous course is indicated by a small canyon buried beneath the flow. Again, the vents were active and a second more vesicular, highly banded basalt, extruded largely from vents northeast of the first, flowed slightly eastward, then, following the line of the new path of the displaced stream to circumvent the first flow, poured out of the canyon almost into Little Whitney Meadow, a distance of nearly 1½ miles. The vents of both these flows are clearly marked by flow banding projecting from vents, flattening in the direction of flow. In one vent the banding may be traced from horizontal to nearly vertical positions. In another case, flow banding dips S60°E at 70° into bedrock at the vent itself.

Second phase.—The second flow, also of massive basalt, has an apparent maximum thickness of 30 feet, probably considerably thicker at the forward edge since remnants lying above the first flow suggest an aggregate thickness of at least 50 feet. Angular granules of quartz and fragments of quartz monzonite are common.

Third phase.—The third phase of eruption follows the pattern of the other eruptive centers, with the building of a small cinder cone superimposed upon a bedrock ridge, extending southeast across the head of Little Whitney Meadow. The cone is composed entirely of pyroclastics, usually cinders of basaltic scoria less than an inch in diameter. The agglomerates dip steeply, from 25–30° on the northeast flank of the cone and more gently on the southeast (Pl. 2, fig. 2). The agglomerates are thicker to the northeast, but the height of the cone above the bedrock ridge appears never to have exceeded 100 feet, making this the smallest of the Toowa Valley cones. A crater from 25–50 feet deep, about 150 yards wide in the NW-SE dimension and 50 yards wide NE-SW, is visible partially filled by a later cone. The crater size is out of proportion to the height and breadth of the original cone.

Fourth phase.—A smaller inner cone of pyroclastic material was built, slightly higher than the first, so that in places the rim of the crater of the first cone is capped by agglomerates of the second.

Fifth phase.—Extrusion of a small basaltic flow from a breach in the south wall of the older outer cone produced a flow about 150 feet long.

Cinders.—Cinders and ash in thin layers spread over a radius of half a mile largely to the north and east of the Little Whitney Center. The phase of eruption which produced the cinders is uncertain, but the large crater found in the first cone is likely the source of the cinders lying upon the surface of the two earliest flows.

Vents

A characteristic in the entire sequence from each volcanic center seems to be the large number of vents from which magma was extruded, particularly in the Groundhog Center. Seldom, apparently, did the same vent erupt twice, but new mouths developed. It is probable, however, that all vents connect at depth to a single magma source. The uniform composition of volcanic products as well as the small area of

Plate 2.—VOLCANIC FEATURES, TOOWA VALLEY

FIGURE 1. GROUNDHOG VOLCANIC CONE FROM SOUTHWEST
Note bedrock ridge on which cone is built.

FIGURE 2. LAYERING IN AGGLOMERATE AND CINDERS, LITTLE WHITNEY CENTER

FIGURE 3. TEMPLETON VOLCANIC DOMES LOOKING EAST ACROSS TEMPLETON MEADOWS
Slight breaks in slope (arrows) mark lowermost ring terrace. (Photo by R. P. Bryson).

FIGURE 1

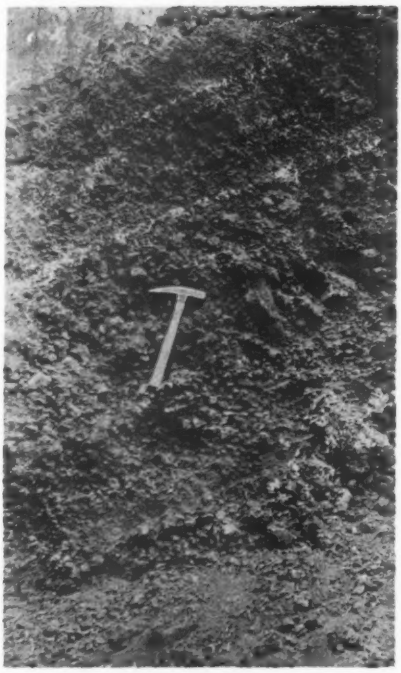

FIGURE 2

FIGURE 3

VOLCANIC FEATURES, TOOWA VALLEY

vent distribution is evidence for this conclusion. The blocky structure of the third phase lavas of Groundhog, with large vertical joints, may account for the repeated eruption through the third phase lavas of magma from many vents.

Templeton Volcanic Centers

Geography

In the far eastern end of Toowa Valley are two volcanic peaks which stagnate the present-day drainage of South Fork of the Kern River. The larger, called Templeton Mountain, rises 9960 feet above sea level and 1500 feet above the floor of Templeton Meadow which surrounds it. A smaller volcanic mass in the Meadow, north of Templeton Mountain, is known as Little Templeton Mountain. It is separated from its larger neighbor by a low saddle where the bases of the two centers merge (Pl. 2, fig. 3). These centers were mentioned by Lawson (1904, p. 321) and briefly described by Knopf (1918, p. 73).

General Description

The Templeton centers are composed of aphanitic, highly banded, pink lava, called latite by Knopf (1918, p. 73). It is the only rock material found on either mountain. A gray facies on the summit of Templeton Mountain is less weathered. The peaks themselves are highly symmetrical in north-south profile, with 23° slopes on the average. East-west profiles are highly asymmetric, with the eastern slope gentler than the west, descending to a quartz monzonite bedrock ridge on which the centers are built. The slopes of both peaks are a jumbled slumped mass of slab rock. Deeply weathered soils encroach upon the mountain bases, merging with slab rock. Slabs are progressively larger toward the summit, a condition typical of Black Butte, in Northern California (Williams, 1934, p. 238). No outcrops positively in place were observed on the Templeton centers, but flow structures that were observed seemed to dip into the peaks at all points. No summit depression is present in either peak; the highest points of each peak are almost the direct projection of the centers of their basal circumference. No lateral flows break the transverse profiles. Concentrically about Templeton Mountain are two terraces, sills or shelf-like rings, 10–20 feet wide. The lower about 400 feet up the mountain is perceptible in Plate 3. The higher is about 1200 feet up slope and is readily plotted in the field.

Origin

The peaks appear to be volcanic domes. The pseudo-terraces concentric about the highest peak are interpreted as products of earlier phases of dome building, comparable possibly to the extension of a telescope tube, with the sleeve of least diameter of youngest invasion. The terraces appear to be best explained by this mechanism. Some slight textural differences were noted in the lavas about each shelf, but these differences may bear no relation to domal extrusion.

Further support of the domal character may be the pressure ridges running east-west which cross Little Templeton Mountain on its summit, extending down its flanks. Here flow banding has east-west strike, stands vertical, and folds over and away from pressure ridges, suggesting lava expulsion along the lines of these pressure ridges.

Monachee Volcanic Center

A single dome, 10 miles south of the Templeton Center, outside of Toowa Valley, is known as Monachee Mountain. It is a single conical hill composed, according to Knopf (1918, p. 73), of latite, and similar in form to the Templeton Peaks, where volcanism was probably contemporaneous.

Swamp Sediments

Templeton Domes are built forward from granitic ridges which extend westward into Templeton Meadows. Exposed in meander scarps at the northwestern base of the Templeton Domes are 60–80 feet of swamp silts, sands, and fine gravels, with some organic layers, deposited beneath the latite in the basin of Templeton Meadows in the pre-Templeton Meadows cycle. The surface of these sediments represents the Toowa Valley level; thus the domes are built on the Toowa surface.

Glacial Gravels

Overlapping flows originating from Groundhog Center are gravels (Q3 alluvium of Pl. 1) interpreted as glacial outwash. Identification is not positive, but striated pebbles are frequent; the gravels are distinctly separable from adjacent stream gravels, both by field relations and textural differences. These unweathered and unconsolidated deposits are assumed to be related to the most extensive Sierran glaciation (Tahoe and contemporaneous deposits). If so, additional inferences regarding relative age are possible.

Table 1.—Sequence of Events

Event	Evidence	Suggested Correlation with Other Events of Kern Basin
Development of Toowa Valley Surface	Erosional surface preserved (Webb, 1946, pl. 3 p. 366	Chagoopa plateau surface
Swamp sediments deposited in Toowa Valley	90–100 feet of sediment in base of Templeton Peaks	
Templeton Domes built	Volcanics cap swamp sediments	Volcanism along Main Kern River (Webb, 1946, p. 368)
Cutting of Inner Toowa Valley	Trenching of swamp sediments exposed below north-west base of Templeton Peaks.	
South Fork Center Volcanism	Flows, and cone built on Toowa and Inner Toowa valley surfaces; flows extend an unknown distance down Golden Trout Creek, overlapped by Groundhog volcanics.	
Further Gradation of Inner Toowa Valley	Overlapping of stream deposits and South Fork flows.	
Canyon cutting in Inner Toowa Valley	Trenching of flows (probably from South Fork Center) near junction with Kern River along Golden Trout Creek	Pre-glacial Kern Canyon cutting completed
Groundhog Center Flows	Groundhog flows fill canyon cut in inner Toowa Valley	
Deposition of glacial gravels	Glacial gravels (outwash) overlap Groundhog flows	(?) Recession of glaciers in Kern River Canyon
Cone Eruptions and Breaching Erosion to present	Cones built on earlier flows	

Suggested Age Relations of Volcanic Sequences

General Statement

Absence of fossil material makes positive dating of these sequences impossible. The relations of (1) Toowa field phases and (2) Templeton Mountain dome building may be partially correlated by some minor physiographic incidents in the evolution of Toowa Valley. Because the Little Whitney center is isolated, it cannot be correlated with other volcanic centers.

Specific Relations

The relations of the western centers of volcanism to those of Templeton Peaks may be inferred. The Templeton Peaks are built on a valley level, dissected by South Fork of the Kern River, exposing swamp deposits in meander scarps of the stream. Quartz monzonite bedrock is also exposed below the sediments. The following sequence is then established (Table 1): (a) These domes are built on the Toowa Valley surface. (b) The present level of

Templeton Meadows is the level of the *inner* valley of Toowa which is now aggraded. (c) Flows from South Fork Center were extruded upon Toowa *and* Inner Toowa surfaces. (d) Across the aggraded inner Toowa valley and across at least one flow from South Fork Center, rest flows and cones from the Groundhog Volcanic center. These relations establish the Groundhog-South Fork episodes (1) not only as post-Toowa Valley surface, but as post-inner-Toowa Valley surface. (2) The Templeton episode is post-Toowa Valley surface, but pre-inner-Toowa Valley surface.

Structural Setting

Structural patterns are not evident in the relations of these volcanic centers, and no generalizations appear justified. Mayo, (1947, p. 501) says of the South Fork and Groundhog cones: "[these] . . . probably lie on an east-west fissure. Both cones are breached toward the northeast, which suggests that the cones were erupted where northeast fissures intersected the east-west fissure."

Cones are commonly breached when flows emanating at or near the cone base cause collapse or breaching by engulfing part of the cone. Intersecting fissures, joints, faults, or other structures is not necessarily evidenced by breaching of cones in a given direction.

Conclusions

Areal mapping of the Toowa Volcanic field has indicated eruptions from centers of volcanism heretofore but inadequately known, and from one hitherto unreported volcanic center in the field. The many separable minor phases of each eruptive center, closely related in time with but small quantities of material in each phase, suggest waning volcanicity. The conclusion is warranted that this field is a late, if not final, episode in the related volcanic activity of the eastern Sierra-southern Inyo region. The relations between late physiographic surfaces and volcanism are clearly shown, establishing details of sequences heretofore obscure. No structural patterns are apparent even with detailed mapping.

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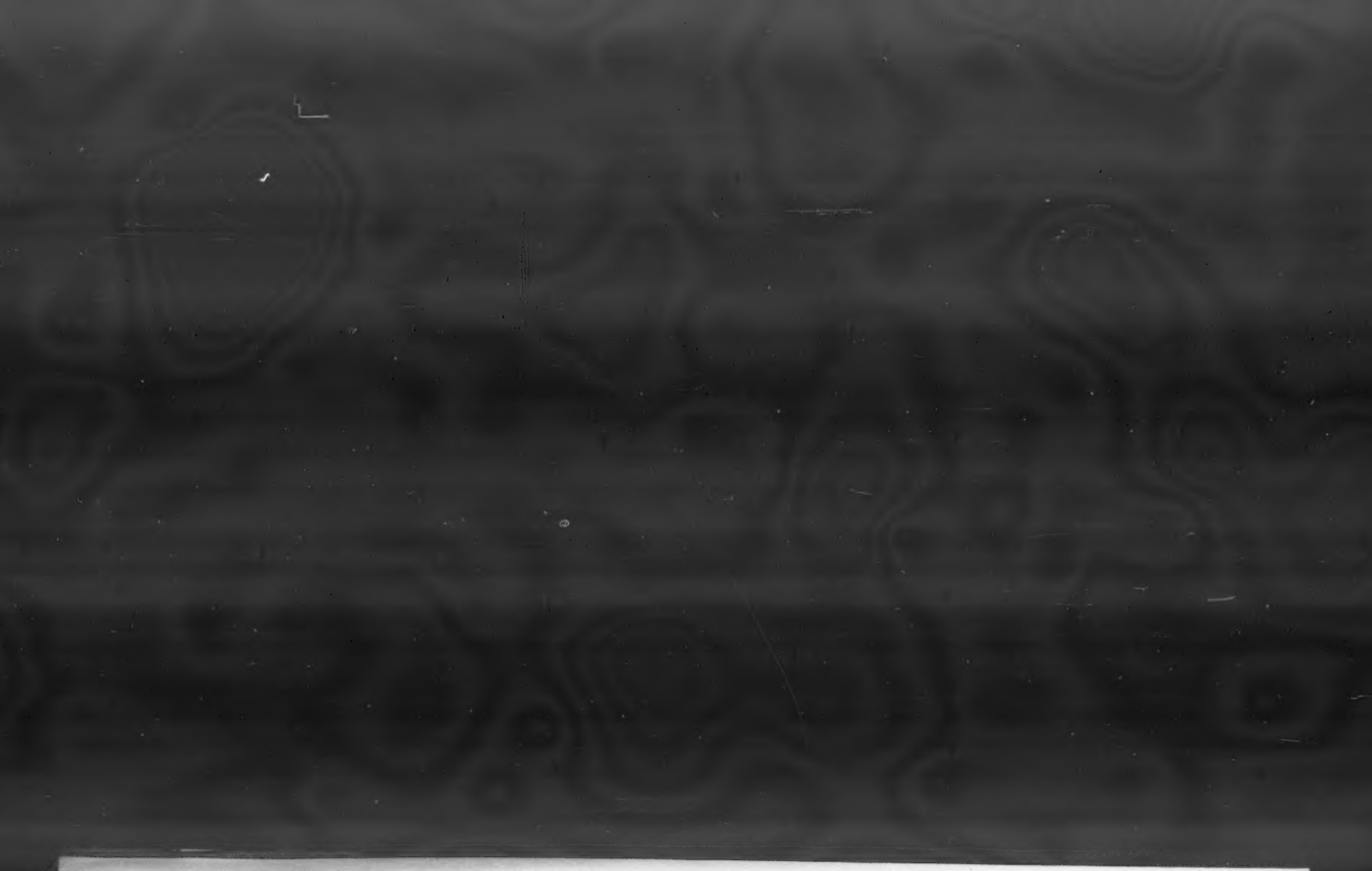

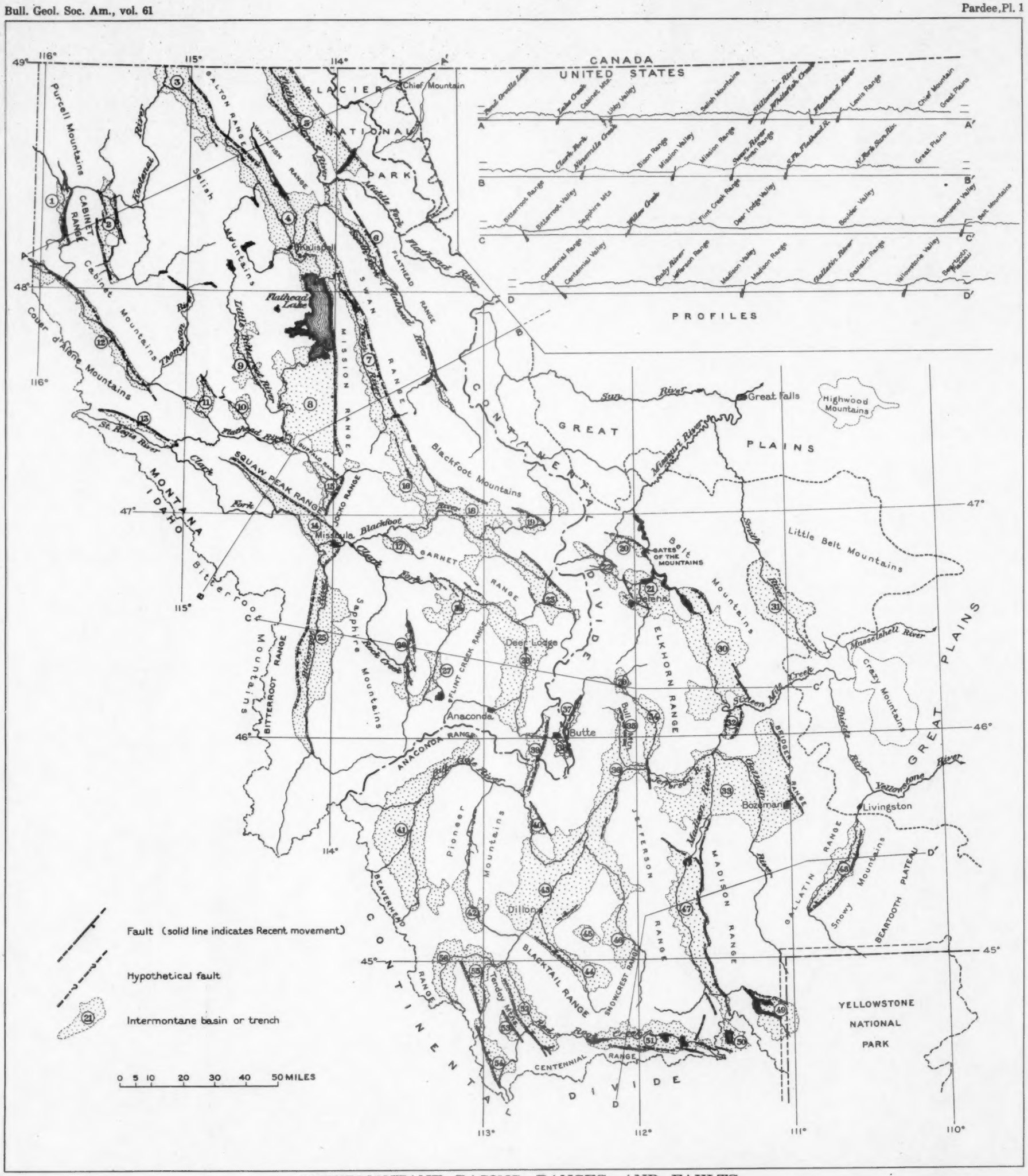

(1) Lake Creek valley
(2) Libby valley
(3) Tobacco Plains
(4) Kalispell valley
(5) North Fork valley
(6) South Fork valley
(7) Swan valley
(8) Mission valley
(9) Little Bitterroot valley
(10) Camas Prairie
(11) Plains basin
(12) Clark Fork valley
(13) Savenac Trench
(14) Missoula-Ninemile valley
(15) Jocko valley
(16) Clearwater valley
(17) Potomac basin
(18) Blackfoot valley
(19) Lincoln valley
(20) Hilger valley
(21) Prickly Pear basin
(22) Silver valley
(23) Avon valley
(24) Flint Creek valley
(25) Bitterroot valley
(26) Willow Creek-Rock Creek Trench
(27) Philipsburg valley
(28) Deer Lodge valley
(29) Boulder valley
(30) Townsend valley
(31) Smith River valley
(32) Clarkston basin
(33) Three Forks basin
(34) Cold Spring valley
(35) Little Whitetail valley
(36) Jefferson valley
(37) Elk Park
(38) Silverbow basin
(39) Divide Trench (Deer Lodge Pass)
(40) Melrose valley
(41) Big Hole basin
(42) Grasshopper valley
(43) Beaverhead valley
(44) Blacktail valley
(45) Sweetwater valley
(46) Upper Ruby valley
(47) Madison valley
(48) Emigrant (Yellowstone) valley
(49) Hebgen (Upper Madison) valley
(50) Henrys Lake basin
(51) Centennial valley
(52) Red Rock (Lima) valley
(53) Muddy Creek basin
(54) Nicholia basin
(55) Medecine Lodge valley
(56) Horse Prairie

INTERMONTANE BASINS, RANGES, AND FAULTS

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LATE CENOZOIC BLOCK FAULTING IN WESTERN MONTANA

By J. T. Pardee

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Abstract

Many of the mountain ranges in western Montana, and the adjoining intermontane basins, are interpreted as chiefly the effects of block faulting like that in the Great Basin. The region was elevated above the sea in late Cretaceous or early Tertiary time; then followed a long period of crustal stability in which a great thickness of rocks was eroded. By Oligocene time the region had been generally reduced to a surface of moderate to slight relief. During the Oligocene and Miocene the drainage became sluggish or ponded, chiefly because of slow crustal movements that outlined the present basins and ranges. Areas corresponding approximately to the present basins became depressed, and in these accumulated the Tertiary "lake beds." Areas of uplift corresponding to the present mountains were eroded and thus contributed land waste and volcanic ash to the "lake beds." In the late Miocene or early Pliocene the surface comprised areas of older rocks that, except for scattered residual peaks and ridges, had been eroded to slight or moderate relief; and areas of the "lake beds" that formed gently sloping or level plains. Excluding the residuals, this surface is called here the Late Tertiary peneplain.

Further leveling of the older rock areas and deposition of the "lake beds" was interrupted by a general re-elevation of the region accompanied by greatly accelerated local crustal movements that relatively elevated the present mountains. These movements continued intermittently and with decreasing intensity through the Pliocene and, except for small displacements on some of the faults as late as the Recent epoch, ceased in early or middle Pleistocene. They are thought to constitute a distinct late stage of the Cenozoic mountain building.

During the halt in the uplift of the mountains, wide stream valleys as much as 1500 feet deep were eroded in the elevated and deformed peneplain. In the basins during this pause, called the Old Valley cycle, the "lake beds" were reduced to gently sloping plains collectively referred to as No. 1 Bench. With renewed uplift the more vigorous streams deepened their channels across the mountain blocks as fast as the surface rose and thus excavated narrow inner valleys or gorges. In this, the Present cycle of erosion, No. 1 Bench of the "lake bed" areas was, in most of the basins, dissected to a series of terraces. The faulting appears to be indirectly related to an axis of compression trending northwestward from Yellowstone National Park. Horizontal compressive forces moved opposite parts of a deeply buried layer of the earth's crust toward this axis. Relief from the compression raised the overlying layer thus causing tensional strains that were relieved by normal faulting and movements away from the plane of the axis.

Introduction

This paper is based upon the writer's observations since 1908 in connection with field work on different projects of the United States Geological Survey. In its preparation the writer has freely drawn upon published reports and he has relied on the topographic maps of the United States Geological Survey for the location, form, and extent of many of the features interpreted as remnants or representatives of a *late Tertiary peneplain* and of still later erosion cycles.

Several of the present mountain ranges and intermontane basins are regarded as the effects of Basin and Range type faulting. Other mountains and basins appear to be simply upwarps or downwarps of the peneplain. The crustal movements are thought to have begun as early as Oligocene time, to have reached a climax in the Pliocene, and then to have gradually declined. Except that, in general, the faults and warps follow the same trend as the late Cretaceous or *early Tertiary* (Laramide revolution) structures, they appear to represent a later and distinct stage of Cenozoic orogeny.

Geography

General Statement

The term western Montana is generally understood to mean the mountainous western third of the State (Fig. 1), a region 100 to nearly 200 miles wide and about 350 miles long extending from Wyoming along central and northern Idaho to British Columbia. Glacier National Park at the northeast, a narrow strip of Yellowstone National Park at the extreme southeast, and large national forests are within its limits. Its area is about 36,000 square miles or nearly one fourth of the State.

Mountains

About three fourths of the region is occupied by generally steep and rugged mountains more or less definitely separated into broad ranges and groups. The higher ranges rise 5000 to 6000

feet above adjacent lowlands and are characterized by sharp peaks, vertical-walled cirques, and other effects of glaciation, developed on a grand scale in Glacier National Park.

valleys having the form and topographic relations suggested by the term intermontane basin. In local usage the term valley is largely restricted to these wide lowlands; the narrow

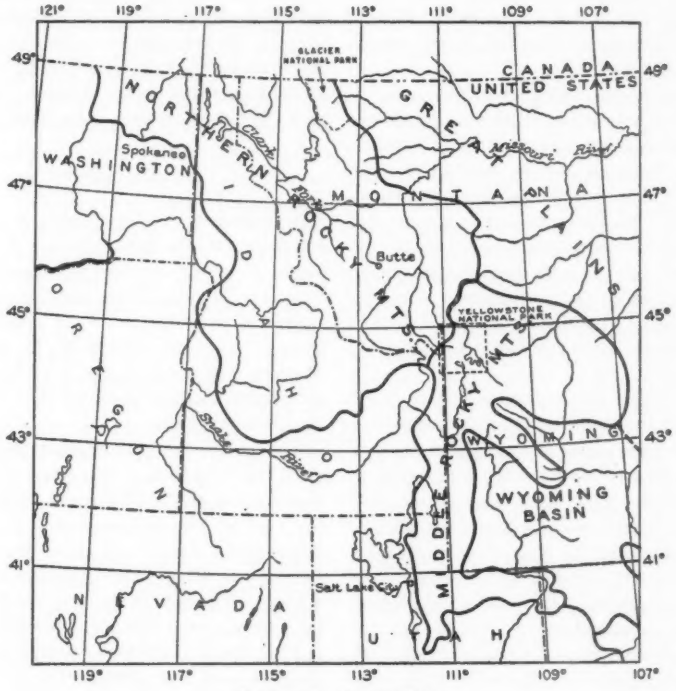

FIGURE 1.—INDEX MAP

The highest altitudes are in the southeastern part of the region: Mt. Cowan in the Snowy Range, 11,190 feet; Electric Peak in the Gallatin Range, 11,155 feet; Lone Mountain and Mount Taylor in the Madison Range, respectively 11,194 and 11,251 feet. In Glacier National Park, Rainbow Peak and Mount Jackson are 9800 and 10,023 feet, respectively, in altitude. From about 10,000 feet in the Beartooth Plateau the general summit altitude decreases unevenly to about 6000 feet in the Cabinet Mountains at the Idaho line, and few peaks reach 9000 feet.

Intermontane Basins

The remainder of the region, approximately 9000 square miles, is occupied mostly by wide valleys that dissect the mountain slopes or form gorgelike outlets of the basins are known as gulches and canyons.

The intermontane basins are irregular in outline (Pl. 1), but in general form many basins suggest ellipsoids. Some are isolated, and others are arranged in groups more or less closely connected by water gaps or low passes. Others are more openly connected in chains or linear groups which Daly (1912, Pt. I, p. 26 *et seq.*, Map sheet 3) named trenches.

Individual basins range from 10 miles or less to 50 or 60 miles in length, and their aggregate length in the outstanding linear group, the Rocky Mountain Trench, including its eastern arm is, within Montana, about 200 miles. Some of the basins are only 2 or 3 miles, and some as much as 20 or 25 miles across at the

widest part (Mission Valley, Beaverhead Valley, and Three Forks Basin; Pl. 1, nos. 8, 43, 33), but most of them average 5–10 miles in width. In area single basins range from 25 or less to 1000 square miles or more (Three Forks Basin). The group that composes the Rocky Mountain Trench, as described, covers about 2000 square miles.

Having entered a basin the traveler, so far as he can see, is hemmed in on all sides by mountains. The usual entrance, a winding narrows or gorge, affords no view to the outside, and the seeming effect is an unbroken mountain rim. Usually the mountains are higher and more rugged on one side than on the others and toward some of the basins present a steep and scenic front rising with precipitous slopes to crags and peaks 5000 or 6000 feet high (Mission Range east of Mission Valley, No. 8; Pl. 4, fig. 3).

In the southeastern and middle parts of the region the floors of the basins are formed mostly of three or more plains in a vertical series that comprises the lowlands or valley bottoms along the streams and the broad moderately elevated intervening areas known as "benchlands." Valley bottoms along the main streams are generally of moderate width, and extend up the principal tributaries to the point at which they issue from the mountains.

The benchland plains descend gradually with decreasing gradients from the mountains toward the interior where they end above terrace escarpments. A comparatively small one at the south of the Three Forks Basin forms the top of an escarpment rising 1000 feet from the Madison River. The more extensive Plains, however, stand 400 to 600 feet above adjacent lowlands. On the average the benchlands occupy about 65 per cent of the basin floors, and the lowlands about 25 per cent. The remaining 10 per cent consists of hilly or other uneven surfaces.

In several basins of the northwestern part of the region, glacial deposits of characteristically uneven contour occupy considerable areas, and, as a rule, terraces are less prominent or extensive. As roughly estimated the floors of the glaciated basins are about half occupied by uneven surfaces; the remainder is about equally divided between terraces of different heights and lowlands including outwash plains.

Like the summits of the mountain groups and ranges the general altitude of the basin floors decreases gradually but somewhat unevenly toward the northwest. The floors of Centennial and Hebgen (Upper Madison) valleys at the extreme southeast average 6700–6800 feet above sea level. To the northwest, Deer Lodge Valley stands at 4800 feet, Mission Valley at 2800 feet; and in Lake Creek Valley at the extreme northwest the altitude is only about 2200 feet.

Drainage

A small area in Glacier Park is drained by tributaries of the Saskatchewan River. Elsewhere the region is about equally divided between the Missouri River and Columbia River watersheds, but because of the irregular course of the Continental Divide (Pl. 1) most of the southern half of the region is within the Missouri basin, and most of the northern half within the Columbia basin.

The headwater of the Missouri River rises in the Centennial Range at a point opposite the easternmost part of Centennial Valley and not far west of the Yellowstone National Park. Successively known as Red Rock Creek, Beaverhead River, and Jefferson River, this stream swings wide to the west, north, and east before joining the Madison and Gallatin rivers to form the Missouri River proper. From there the river continues northward until well out of the mountains.

West of the Continental Divide most of the region is drained by the Clark Fork of the Columbia. This stream heads in Silver Bow basin south of Butte and from there, locally known in succession as Silver Bow Creek, Deer Lodge River, Hell Gate River, Missoula River, and Pend d'Oreille River, follows a general northwest course and enters the Columbia north of the Canadian boundary and not far from the northeast corner of Washington. A relatively small area in the extreme northwestern part of the region drains to the Kootenai River, a more northern branch of the Columbia.

As a rule the main stream of each intermontane basin occupies a medial position where it receives tributaries from the mountains on both sides. It may have its source within the basin or elsewhere but it escapes through a gorge or narrows.

Geology

Older Formations

The rocks of western Montana may be classified into two groups that differ in general character and are separated by a marked erosional unconformity. The older group is marine and continental land-deposited sedimentary beds and metamorphic and igneous masses that range from Precambrian to early Tertiary. The younger group includes extensive areas of Tertiary volcanic breccias and lavas but consists mainly of Oligocene and Miocene freshwater clays, sands, and gravels, and beds of volcanic ash which compose the Tertiary "lake beds". Locally these deposits are overlain by lava flows, particularly toward the south and southeast.

In the northern half of the region the older group consists almost exclusively of sedimentary rocks of the Precambrian Belt series (Willis, 1902, p. 305–352; Calkins, 1909, p. 58–91; Deiss, 1943a, p. 205–262; Clapp, 1932; Gibson, 1948). These formations are mostly argillites and quartzitic sandstones that tend to merge rather than to form separate units. They aggregate a great thickness. In places relatively small bodies of intrusive rocks are present; most of them are dikes and sills of diorite or related types. All are about equally resistant to erosion and in general are not marked by any striking differences in details of topography. The bedded rocks are folded into large open folds and extensively displaced by normal and thrust faults. Along the eastern margin of the region the Lewis overthrust has moved older rocks 20 miles or more eastward over younger beds.

In the southern part of the region the older group is a complex assemblage of Precambrian gneiss and schist, the Archean and Algonkian of Peale (1896); and thick to thin beds of Paleozoic and Mesozoic limestones, shale, and sandstones locally altered to hornstones, quartzite, and other metamorphic products. The group includes several intrusive granitic bodies, among them the extensive Boulder batholith and, along the Bitterroot Range, part of the still greater Idaho batholith. The rocks differ in their resistance to erosion; some yield smooth slopes or depressions, others knobs, walls, chimneys, or other rugged forms.

The bedded rocks are rather intensely deformed in closely packed tightly compressed folds, some of them inclined or overturned, and in addition they are displaced by steep normal and reverse faults. The trends of these structures vary widely but are mostly northward. In addition large blocks have been thrust eastward on a southward continuation of the Lewis overthrust and on other thrust planes.

Throughout the region the rock structures appear to be chiefly the effects of compression normal to a northwest-southeast axis. Variations in trend in the southern part appear to be related to the granitic intrusions. The difference in scale between the structures of the northern and southern parts of the area may be explained as due to differences in the thickness and competence of the bedded rocks and partly to the effects of the intrusions. The thick, relatively competent formations of the northern part yielded in larger folds and faults, the comparatively thin and more or less weak beds of the southern part giving way in small structures.

Secondary structures include a number of relatively small faults oblique in trend to the larger ones and doubtless the results of local adjustments. Among these are a number of small tension fractures that trend eastward or at right angles to the main structural axes and have caused little or no displacement.

Younger Formations

Eocene conglomerate and early and middle Tertiary gravels.—Cemented gravels of probable Eocene age occur in the Madison Range on Sphynx Mountain (Peale, 1896) and in the Philipsburg quadrangle, along Rock Creek, Warm Spring Creek, and on the southeast slope of the Anaconda Range (Emmons and Calkins, 1913, p. 134, 135). Along Rock Creek west of Philipsburg Valley they form bluffs and chimneys (The Hoodoos) several hundred feet high.

Early and middle Tertiary gravels occupy considerable areas in Red Rock Valley and neighboring basins and, in places, extend to the top of the Beaverhead Range and other mountains in the southern part of the region. They are largely well-rounded pebbles and cobbles and appear to be several hundred feet thick.

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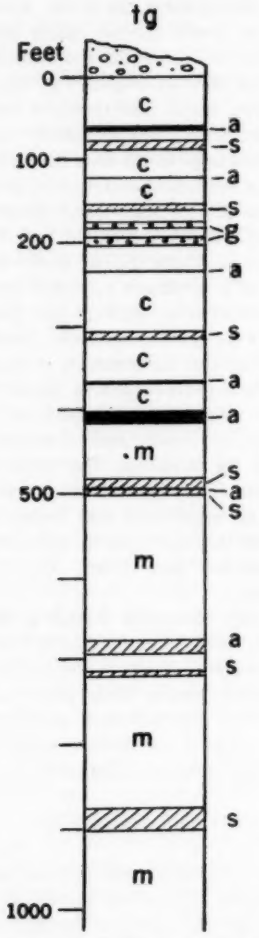

FIGURE 2.—COLUMNAR SECTION OF TERTIARY "LAKE BEDS"

In escarpment east of Madison River, 10 miles south of Three Forks, Montana.

a. unmixed ash
c. clay
g. gravel
m. mixed ash and sand
s. cross-bedded sand and sandstone
tg. terrace gravel; Bench No. 2

Miocene sediments occupy some of the basin areas in the southern two-thirds of the region and, in the northern one third, are present in basins drained by the north and south forks of the Flathead River. Outside the basins, however, they have not been identified except in one or possibly two places. A small patch, apparently elevated by the fault at Little Pipestone Creek, occurs well up on the range (Continental Divide) west of Jefferson Valley (Atwood, 1916, Pl. XXXVII A).

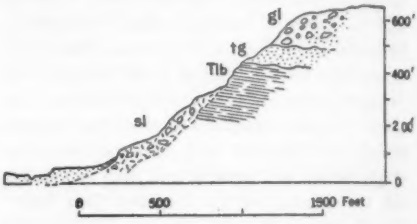

FIGURE 3.—SECTION IN BLUFF EAST OF MADISON RIVER, MADISON VALLEY

gl. glacial outwash
tg. terrace gravel
Tlb. Tertiary "lake beds"
sl. slide

The "lake beds" are mostly fine-grained water-laid tuff or volcanic ash mixed or interbedded in varying proportions with generally fine-textured land waste chiefly sand and clay, but including in places a bed of gravel. An almost universal feature is the occurrence of relatively thin beds of pure or unmixed ash.

In many basins the "lake beds" yield Oligocene or Miocene vertebrate remains (Douglass, 1899; 1900; 1902; 1903; 1905; 1908), and Oligocene plant remains have been found in the Missoula and Townsend valleys (Jennings, 1920). Lignitic coal occurs in several basins (Pardee, 1913, p. 229–244; Erdmann, 1947).

In the Three Forks basin (Peale, 1896) exposures of the Tertiary "lake beds" comprise 800–1000 feet and indicate a possible maximum thickness of 2000–2500 feet. Exposures in terrace escarpments examined by the writer along Madison River south of Three Forks are about 1000 feet thick and consist chiefly of volcanic ash, partly or completely altered to a claylike material, mixed with fine quartz and mica sand (Fig. 3). Irregularly through the column are relatively thin beds of unmixed ash, cross-bedded sand and sandstone, and gravel. The cross-bedding was formed by northward-flowing streams, and the nearest source of the micaceous sand is in the Madison Range to the south.

As exposed in terrace escarpments in the middle and eastern parts of the basin, the Tertiary "lake beds" dip gently eastward or toward the Bridger Range. In the Deer Lodge valley north of Deer Lodge an east-facing escarpment formed of horizontal Tertiary "lake beds" is 500 feet high.

In Townsend Valley (Pardee, 1925, p. 22–30) 300–400 feet of Oligocene beds is exposed in several places. Exposures along Beaver Creek consist mainly of tuff and volcanic conglomerate 2800 feet thick. Miocene beds, poorly exposed, consist mainly of sand and gravel derived from rocks of the older group of formations exposed in the neighboring mountains. They are separated from the Oligocene beds by an angular unconformity. They are less extensive than the Oligocene beds, and their maximum thickness (estimated) is 500–700 feet. In the middle and eastern parts of Townsend basin the Tertiary "lake beds" form small open folds that trend north or northwest; the dips range from 8° to 25°. In places the beds are upturned at the foot of the Belt Mountains along the east and at Sixmile Creek are exposed in fault contact with the older rocks. In the southeastern part of the basin the beds are displaced by a series of normal faults (Pardee, 1925, p. 16, Fig. 4) with downthrows of 50–150 feet toward the west.

In the Flint Creek Valley (Pardee, 1913, p. 9) a maximum thickness of 2100 feet is indicated for the Oligocene, and 1000 feet for the Miocene. In the northwest corner of this basin the beds are deformed by small folds and downthrown toward the basin by faults trending northwest. Dips on these structures are 30° or less. In widely scattered exposures elsewhere the beds, as a rule, slope gently toward the interior of the basin.

In the southeastern part of Missoula Valley coal-bearing Tertiary "lake beds" are bent into an open syncline that lies next to the range at the northeast. Along the mountain front the upturn on this structure is as steep as 70°. Dips on the outer flank are 40° or less. Elsewhere in the basin the beds, as exposed in a few places, are moderately inclined to the northwest and northeast.

As indicated by scattered and incomplete exposures the "lake beds" in other basins are generally similar in composition and comparable in thickness. As a rule, they are gently inclined either toward one side or the other or from both sides toward the interior where they are horizontal.

In the basins north of Missoula Valley and west of the Mission Range the "lake beds" have not been definitely identified. Deposits in those areas that may be Tertiary are: a rusty sandstone exposed at the southern edge of the Mission Valley; a sandstone with a thin bentonitic layer penetrated at a depth of 1000 feet by a drilled well near the middle of the same basin, and a rather coarse water-laid tuff in the northern part of Little Bitterroot Valley, its beds inclined about 10° S. In the same category are certain gravels, some of them iron-stained and partly cemented and some containing cobbles that, in place, have become softened or decayed. These are exposed in or near the margins of the Plains and Savenac basins and at the northern end of Jocko Valley.

Tertiary volcanics.—Except for some small patches west of Flathead Lake (Shenon and Taylor, 1936), no Tertiary volcanic rocks are known in the northern half of the region. In the southern half such rocks are rather widely distributed. They are mostly confined to the mountains but in places extend into the basins. Andesitic flows and tuffs of probable Miocene age underlie several hundred square miles in the Gallatin Range (Peale, 1896) and the Snowy Range or Beartooth Mountains north of Yellowstone Park (Weed, 1893a). On the eastern flanks of the Gallatin Range these rocks descend to the margin of Emigrant (Yellowstone) Valley and pass beneath its superficial deposits. Large areas of similar rocks occur on Bull Mountain (Weed, 1912), in the northern part of the Belt Mountains (Lyons, 1944, p. 455–471), and in the unnamed range at the end of the Beaverhead-Jefferson basin south of Dillon. Lavas continuous with those of the Snake River Plain extend up the south side of the Centennial Range to its crest, and rocks correlated with them, and evidently displaced by the Centennial fault, occur on the slopes north of Centennial Valley. Andesitic and rhyolitic lavas occupy considerable areas in the Garnet Range (Pardee, 1918b) and the Continental Divide north of Butte (Weed, 1912). A large area of rhyolite at the southeast end of the Gravelly

(Jefferson) Range forms a gently sloping low plateau.

Quaternary formations.—Pleistocene deposits, described by Alden (in preparation) as chiefly drift, outwash, and lacustrine silt, largely form the basin floors in the northern half of the region. Ridges and hills of glacial drift are conspicuous in the Blackfoot Valley, in the Mission basin south of Flathead Lake (Polson moraine), and in the eastern part of the Kalispell Valley. Outwash gravels and related alluvial deposits form plains and extensive terraces in the Tobacco Plains and Kalispell Valley, and low terraces of glacial lake silt are extensive in the Missoula, Mission, Little Bitterroot, and Plains valleys.

In the southern half of the region moraines and outwash gravel overspread much of the Yellowstone (Emigrant) Valley (Weed, 1893b). Elsewhere glacial deposits within the basins are limited to the relatively small moraines of local glaciers, chiefly from the Madison, Beaverhead, Anaconda, Flint Creek, and Bitterroot ranges. Gravels, which may be Pleistocene but not necessarily glacial, veneer the terraces. Relatively small flows of Pleistocene or Recent basalt occur in the Emigrant and Red Rock basins. Recent alluvium underlies the bottom lands or flood plains and forms cones and fans at the base of the mountains.

Physiography

General Description

Western Montana (Fig. 1) occupies approximately the eastern third of the physiographic province called the Northern Rocky Mountains (Fenneman, 1931, p. 183–224). As generally interpreted, the history of this province begins in late Cretaceous or early Tertiary time with folding of the rocks and elevation of the surface above the sea (Laramide revolution). During the Eocene, erosion reduced the province to a generally low surface of moderate relief. The drainage was free and swept away all land waste except the patches of relatively coarse gravels mentioned under Geology.

During the Oligocene and part of the Miocene drainage was sluggish; as a result large areas, approximately equivalent to most of the present intermontane basins, became overspread with the sedimentary deposits called Tertiary "lake beds." To some extent the slowing of the drainage may have been caused by lava eruptions (Atwood, 1916, p. 711) but is thought to have been chiefly the effect of crustal deformation. The areas of deposition were slowly and intermittently depressed as indicated by the alternating coarse and fine sediments (Fig. 2) and local beds of coal in the "lake beds."

The "lake beds" occupied approximately the areas of most of the present intermontane basins, but, as indicated by land waste throughout the section, they did not far overspread the surrounding areas. In particular the Miocene deposits are chiefly fine to moderately coarse gravels derived from lands that were exposed at or near the present margins of the "lake beds".

By the time deposition of the "lake beds" ceased, most of the areas of older rocks had been reduced to gently sloping or level surfaces. These and the surface of the "lake beds" formed the Late Tertiary peneplain.

As the basins became outlined and depressed in Oligocene and Miocene time, the present mountains were elevated, but the crustal movements were slow, and the uplifts were probably reduced about as fast as they grew, a conclusion supported by the occurrence of land waste in the "lake beds". Peneplanation was not seriously interrupted until the movements became accelerated at about the end of the Miocene.

In a succeeding period that extended into the Pleistocene the more rapid and extensive crustal movements, including warping and faulting, effected a general differential re-elevation of the region and the uplift of the present mountains.

During a halt in the uplift established streams eroded wide valleys (Old Valley Cycle) to moderate depths. When upward movement was resumed the weaker streams became diverted and their identities lost; remnants of their abandoned valleys form some of the present wind gaps. The more vigorous streams deepened their channels as fast as the mountains rose and thus excavated narrow inner valleys or gorges.

In the basins the original surface of the lake beds was cut away during the Old Valley Cycle, and a lower plain was exposed (No. 1 bench). This surface was largely cut away in the present cycle, exposing still lower plains that form a

series of terraces and the present valley bottoms.

While dissecting the "lake beds," superimposed streams (Atwood, 1916, p. 106) excavated the canyon of Jefferson River (G, Fig. 3) and other gorges across buried ridges of the older rocks.

Late Tertiary Peneplain

At the end of the "lake-bed" period the land surface comprised the areas, presumably flat or gently sloping, that were underlain by the Tertiary sediments, and areas of the older rocks that had been exposed to erosion since early Eocene time.

Erosion surfaces representing one or more cycles have been recognized on the older rocks at several places in the mountain province.

On the Wind River Range and neighboring mountains of northwestern Wyoming mesalike summits and parallel surfaces several hundred feet lower are interpreted, respectively, as remnants of a peneplain and the less extensive plains of later uncompleted erosion cycles (Westgate and Branson, 1913, p. 144–147; Blackwelder, 1915, p. 193–195, 310; Baker, 1946, p. 586–591).

In the mountains of south-central Idaho an erosion surface is represented by even-crested ridges and here and there broad flat summits at 8500–10,000 feet altitude (Umpleby, 1912, p. 139–142; 1913a, p. 22–26, Figs. 2, 3, 4; 1913b, p. 14–16, Pl. III A, B; Pl. IV A). Rock-cut terraces parallel this plain at lower levels. To the north in the Clearwater Mountains, Lindgren (1904, p. 14, 59, 60, Fig. 4) and others have been impressed by the resemblance of the upland to a dissected plateau which here and there carries an isolated summit or chain of peaks. In distant views the ridge tops appear to merge at 7000–8000 feet altitude into an undulating plain (Shenon and Reed, 1934, p. 7; Reed, 1937, p. 3; Capps, 1940, p. 4) that rises gradually southeastward. Into this surface the canyons of Salmon River and other main streams are cut as deep as 5000 feet. Within the limits imposed by a 200-foot contour interval, the Lolo topographic map of the United States Geological Survey indicates moderately sloping uplands as much as 2 miles wide that give place abruptly to steep descending slopes. In a selected rectangle of 200 square miles athwart the canyon of the Lochsa River at Grave Butte, the uplands form nearly 20 per cent of the total area. They indicate a former surface made up of rather gently contoured hills and valleys with a local relief of 1000 feet.

The appearance of an undulating plateau is carried northward across the Coeur d'Alene Mountains and into western Montana by smooth-topped ridges of accordant height (Calkins, 1909, p. 14); the general land surface descends in that direction to about 6000 feet at the Idaho-Montana divide. Even-crested ridges at that height extending well out toward the western limit of the upland represent a summit peneplain (Anderson, 1939, p. 751, 752).

In western Montana surfaces interpreted as remnants of a Late Tertiary peneplain developed on the older rocks are the even-crested divides and spurs commonly topped with flat or gently sloping surfaces of widespread occurrence on the different ranges and mountain groups. Among the higher and more extensive uplands are undulating surfaces at 9000 to 10,500 feet altitude on the Beartooth Plateau (Snowy Range) south of the Yellowstone National Park interpreted by Bevan (1925, p. 563–587) as representing a peneplain of probable Pliocene age. They form the tops of spurs west of the Boulder River and the tops of the divides east and west of that stream (Pl. 5, D) east of Hell Roaring Creek, south of Grizzly Creek, and also the Lake Plateau south of Mt. Douglas. They are developed on a Precambrian crystalline complex and later volcanics and range in area from 1 to 10 or 20 square miles. Among the peneplain remnants in ranges to the west and north are: tabular summits at 9000 feet altitude on the main divide of the Gallatin Range; the broad rolling tops at 8000–9000 feet of spurs that project westward along Squaw, Elkhorn, and Buffalo Horn creeks (Pl. 5, B); and the even crest at 7500–8000 feet altitude of the ridge north of Trail Creek. These surfaces are developed on andesitic lavas and folded Cretaceous sedimentary beds. In the Madison Range they include: flat to gently sloping areas at 9000 to 9400 feet altitude on the main divide and east-projecting spurs north and south of Taylor Creek and Buck Creek (Pl. 5, I). These surfaces are developed across deformed Mesozoic shales, sandstones, and limestones. In the

Gravelly Range (southern part of Jefferson Range) they form wide, gently rounded surfaces at 7400–8400 feet altitude on main divide south of Old Baldy Mountain and on spurs projecting eastward along Wigwam, Morgan, Cherry, and Ruby creeks (Pl. 5, I), developed on inclined Paleozoic and Mesozoic sandstones, shales, and limestones. The Continental Divide south of Butte carries gently sloping surfaces half a mile to 2 miles wide at 7300–8000 feet altitude. Similar surfaces descend gradually to 6000 feet on north-projecting spurs east and west of Basin Creek and Blacktail Creek. The underlying rock is granite. Between Butte and Helena the Continental Divide and its main spurs carry flat and gently sloping areas half a mile to a mile wide in many places, particularly at the headwaters of Cataract and Basin creeks. They are developed on granite and later volcanics. In the Belt Mountains north and west of Fort Logan flat to gently sloping surfaces 1 to 3 miles wide at 6300 to 7100 feet altitude top the main divide and spurs north and south of Rock Creek. They cut across shales and sandstones of the Precambrian Belt series. In the Little Belt Mountains south of Neihart, flat to gently sloping surfaces half a mile to 2 miles miles wide at 7000 to 8000 feet altitude form the main divide and several spurs. They cut across folded Precambrian and Paleozoic sedimentary rocks. In the Ruby Range gently sloping surfaces at 7000 to 8200 feet altitude top the main divide and the spurs north and south of Sweetwater basin and east of Sweetwater Creek. These are developed across Precambrian gneiss and schist. In the Pioneer Mountains south of Vipond a flat (Vipond Park) (Pl. 2, fig. 2) 2 miles wide at 8000 feet altitude on an east projecting spur is developed on granite. In the Flint Creek Range wide flat or gently sloping shoulders at 8400–8700 feet altitude north and south of Lost Creek and the flat top of Cable Mountain are cut across folded Precambrian and Paleozoic beds (Atwood, 1916, p. 707–708, Pl. XXXII A, B).

East of Monida Pass remnants of the peneplain are carried on the crest of the Centennial Range at 8000–9000 feet altitude and on the backs of spurs that descend gradually southward to the Snake River Plain. They are developed chiefly on Miocene lavas. The even crest at about 9000 feet altitude of Blacktail Range is a gently sloping surface eroded across Mesozoic sedimentary beds. Southward it descends on the backs of spurs toward Red Rock Valley. Southwest of Horse Prairie basin (Pl. 1, No. 56) the peneplain is represented by the even crest of the Beaverhead Range (Atwood, 1916, p. 707–708, Pl. XXXIV, A).

The Garnet Range and, west of the Clark Fork, the Sapphire, Bitterroot, and Coeur d'Alene mountains are broad uplands whose general summit form and altitude are determined by remnants of the peneplain. In the Garnet Range the general summit, at 6000 to 6500 feet, is marked by flat or gently rounded ridge tops and mesalike summits mostly less than half a mile wide. These features are so numerous that they occupy 5–10 per cent of the upland area and, where seen from distant and slightly higher points, seem to form a continuous surface with here and there a projecting ridge or peak (Pardee, 1918b, p. 162, 163). As thus represented the peneplain is slightly convex upward in a cross profile of the range (Pl. 5). On the north side of the range, it descends for short distances on several spurs that project toward Blackfoot valley.

In the Sapphire Mountains the peneplain is represented by a gently sloping upland (Pl. 2, fig. 1) west of Willow Creek Valley and, in general, by surfaces that fall in place with an undulating plain 6000 to 7000 feet in altitude. Toward the west it descends gradually for longer or shorter distances on the backs of several spurs projecting into the Bitterroot Valley (Pl. 5).

North of Lo Lo Creek the Bitterroot Mountains, like the Garnet Range and the Sapphire Mountains, look like a maturely dissected undulating plateau, because of the occurrence of similar though generally somewhat narrower areas of flat or gently sloping surfaces widely distributed on top of the main divides and spurs. As determined by these features the peneplain rises gradually from an altitude of 4000–4500 feet, at the top of the slope west of the Missoula-Ninemile Valley, to about 6500 feet on the divide east of Petty Creek. From the valley of that stream westward to the main divide along the Idaho-Montana line, the altitude of the peneplain is 6000–7000 feet.

Southwest of the Clark Fork below Thompson Falls, the peneplain rises gradually from

4000–5000 feet altitude at the top of a steep slope to 6500 feet above an escarpment that descends to Sevenac valley. Beyond Savenac valley the peneplain again rises westward from an altitude of 6000 feet to about 7000 feet at places along the main divide of the Coeur d'Alene Mountains; in the Bitterroot Mountains near the western limit of the region the peneplain, as represented by even-crested ridges, is 5000–7000 feet in altitude (Pl. 5, M).

The Cabinet Mountains comprise a broad upland west of the Lake Creek Valley (Pl. 1, No. 1) and a higher ridge, the Cabinet Range, which extends southward along the opposite (east) side of that depression and continues southeastward along the Clark Fork Valley as far as Plains basin (Pl. 1, No. 12). On the upland west of Lake Creek Valley relatively small flat or gently sloping areas are widely distributed on the main divides and spurs. As thus determined the peneplain rises from about 5000 feet near the valley to about 6500 feet at a point 3 miles beyond the Idaho boundary (distance of 10 miles). East of Lake Creek Valley the Cabinet Range rises abruptly to a general altitude of 7000–7500 feet with a few higher peaks (Snowshoe 8712 feet). Severe glacial scouring of the upper slopes has left only sharp ridge tops as possible representatives of the old surface.

Along the Clark Fork Valley the Cabinet Range rises steeply to a general crest at 6000–6500 feet altitude with here and there a peak a few hundred feet higher. The northeast or back slope is maturely dissected, and its general surface descends about 1000 feet in 6 or 7 miles. The deep gorgelike valleys of Vermilion and Thompson rivers cross it; the local relief of the intervening stretches is about 1000 feet. Except for an occasional sharp peak or ridge, the divides and spurs are smooth and probably represent the peneplain.

The Selish Mountains comprise several closely spaced moderately high ranges and other uplands between the Cabinet Mountains and the valleys to the northeast (Pl. 1, Nos. 3, 4) that form the Rocky Mountain Trench. East and west of Little Bitterroot Valley ranges of this group rise 1000–2000 feet or to altitudes of 4000 to 5000 feet and present a mature topography. Their summits are smooth, as a rule, and from the sides irregular spurs project well out into the valley. In detail the slopes are uneven with ridges and knobs expressive of structure and differential resistance. North of the Little Bitterroot Valley the ranges become irregular or indefinite and over most of the area merge in a single composite upland. The general upland surface ranges from 4000 to 5500 feet in altitude. At the northwest it descends gradually to 3500 feet along Tobacco Plains Valley. Here and there a sharp peak rises a few hundred feet above the general surface, and a few streams have cut sharp valleys as much as 2000 feet deep. As a rule, however, the local relief is less than 1000 feet, the slopes are gradual, and the topography mature.

The Galton and Whitefish ranges together form a broad upland, the general summit of which descends gradually eastward from a crest at 7000–7500 feet altitude overlooking the Rocky Mountain Trench. Severe local glaciation has destroyed all vestiges of the peneplain, and the form and position of that feature can be surmised only from ridge profiles. Similar considerations apply to the Mission, Swan, and Flathead ranges and the mountains of Glacier National Park.

Deformation of the Peneplain

General discussion.—Late Tertiary peneplain was deformed extensively in western Montana by faulting and warping incidental to the general re-elevation that followed the deposition of the "lake beds".

Several of the ranges in western Montana present the bold, straight, and abruptly rising fronts and other features characteristic of uplifted fault blocks described by Gilbert (1890, p. 340–355), Davis (1903, p. 129–177), Louderback (1904; 1924; 1926), Lawson (1912, p. 193–200), and Blackwelder (1928, p. 294–308). Observable dislocations of the rocks or exposures of the fault plane support the physiographic evidence. The adjoining basins represent complementary downthrown blocks, each pair separated by a steep normal tensional fault. Dislocated parts of the peneplain suggest that the downthrow on several of the faults amounts to 5000 feet or more.

Madison Range fault.—A Recent scarp at the western base of the Madison Range traces a normal fault that has depressed the adjoining

Madison basin (Pl. 1, No. 47). The scarp, about 40 miles long, measures a vertical displacement of the present surface of between 10 and 30 feet or more. Earlier and more extensive displacements by the same fault are indicated by the scarplike mountain front above. Total relative downthrow, as estimated from displaced parts of the Late Tertiary peneplain, is several thousand feet.

Madison basin is an intermontane depression about 55 miles long and 5 to 12 miles wide. The altitude of the basin floor increases from about 5000 feet at the north to 7000 feet at Reynolds Pass on the southern end. On the east the Madison Range rises abruptly and steeply to peaks 4000–5000 feet above the basin floor.

The Jefferson Range along the western side of the basin, though nearly as high as the Madison Range, is much less steep and abrupt. Opposite the northern part of the basin it is crossed by a broad low pass leading to Alder Gulch (famous in gold-mining history) and to Jefferson Valley beyond. That part of the Jefferson Range south of the pass is known as the Gravelly Range.

Three Forks basin (Pl. 1, No. 33) to the north is separated from Madison basin by a broad low ridge, the continuation of a spur from the Jefferson Range. On the south two broad wind gaps, Reynolds Pass and Hidden Lake Pass, lead to Henry's Lake basin and Centennial basin, respectively (Pl. 1, Nos. 50, 51). A moderately high unnamed mountain range rises between the two gaps and extends south for a distance forming the Continental Divide.

The Madison River enters near the southern end of the basin from a gorge, known as Upper Madison Canyon, cut through the Madison Range. The river crosses to the west side of the basin, turns north, and for several miles closely follows the base of Gravelly Range. Farther north it gradually shifts to the middle and finally to the northeast corner of the basin where it escapes to Three Forks basin through another gorge, Lower Madison Canyon. Along its course through the basin the river receives several streams from the mountains on either side. The largest of these, the West Fork, drains the southern parts of both the Gravelly Range and the Madison basin and joins the river where it turns north at the base of the Gravelly Range.

Tertiary "lake beds" underlying terrace gravel are exposed at several places in the escarpments, particularly in those facing the river. In the southwestern part of the basin below the mouth of Squaw Creek an escarpment east of the river exposes 100 feet of distinctly bedded volcanic ash (Fig. 3) that dips 6°–10° E. toward the Madison Range. Discontinuous exposures elsewhere indicate that the lake beds in general dip gently eastward.

Madison Range is a broad massive elevation composed chiefly of Precambrian gneiss and schist and deformed Paleozoic and Mesozoic sedimentary rocks. A large body of intrusive "porphyrite" (andesitic porphyry) is present in the northwestern part, and a small area of Eocene (?) conglomerate lies upon an eroded surface of older rocks at Sphynx Mountain (Peale, 1896; Condit, Finch, and Pardee, 1928, p. 189–203). The structural trend is mainly northward parallel to the axis of the range but includes some local variations to the northeast and west-northwest.

The mountains west of the basin are formed mostly of the same rocks as the Madison Range. At the south an extensive sheet of rhyolite covers the lower eastern slope of Gravelly Range, Hidden Lake Pass, and a bordering strip along Madison basin above the mouth of the West Fork. The lava sheet descends eastward with a slope gradually decreasing from 10° to 6° or less. In the range it rests on an eroded surface of Mesozoic and older rocks. At Cliff Lake and some other places at the edge of the basin the lava sheet overlies Tertiary lake beds."

Back (east) of the mountain front, Madison Range looks like in general a broad dissected platform or plateau (Pl. 5, B). This form is given by flat or gently sloping surfaces on the backs of divides and high spurs of accordant height. These surfaces cut across the rocks irrespective of composition or structure and represent a formerly continuous surface of worn-down relief that is referred to here as the Late Tertiary peneplain.

The Recent scarp marks a displacement along the base of the Madison Range from Jack Creek southward nearly to Reynolds Pass, a distance of about 40 miles. In this course the scarp is separated into several segments arranged in a regular en echelon order (Fig. 4). It is formed mostly in unconsolidated alluvial and glacial deposits; its slope therefore is the

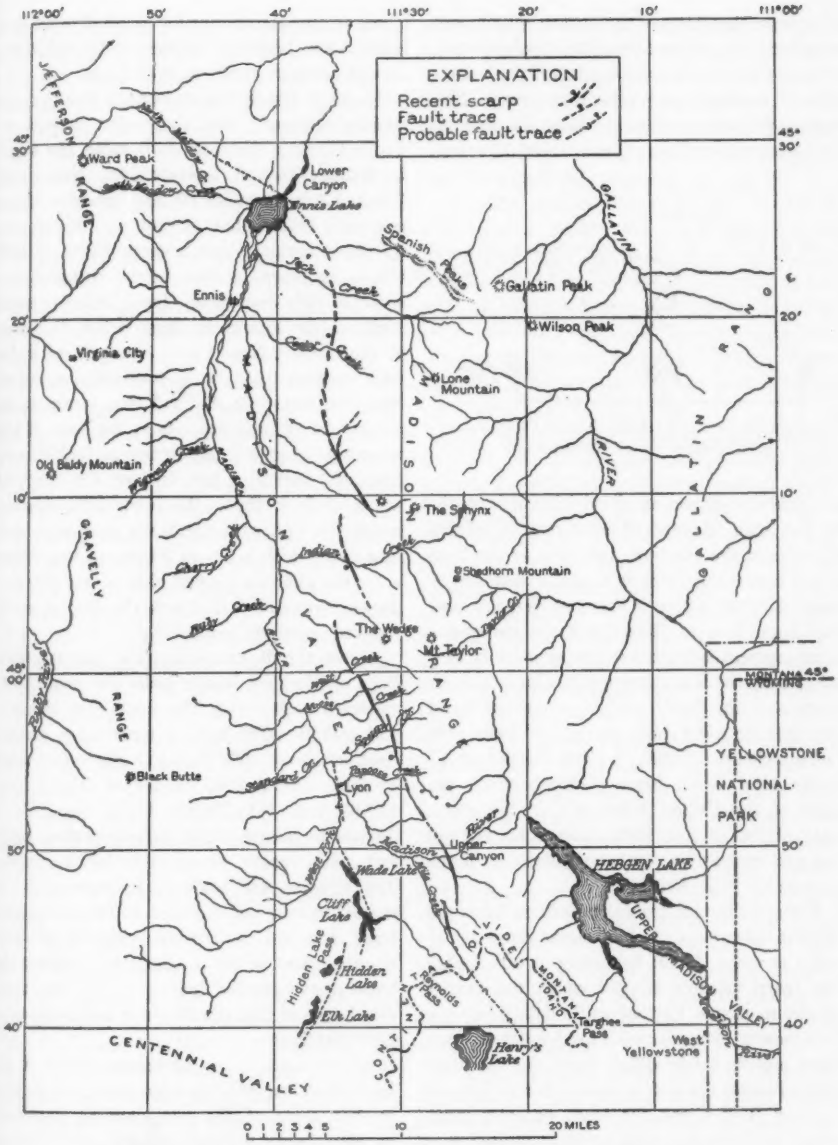

FIGURE 4.—PLAN OF RECENT SCARP OF THE MADISON RANGE FAULT

angle of repose for loose materials—30°–35°. In a few places (south of Jack Creek and south of Slide Creek) it coincides with rock surfaces that dip 45°–50° toward the basin. The scarp may be seen to good advantage where it crosses an alluvial plain and a terrace escarpment south of the Madison River just below the gorge from which the stream enters the basin (Pl. 3, fig. 1). The vertical displacement is about 20 feet, and the nearly exact alignment

of the separated parts of the terrace escarpment indicates little or no horizontal displacement. At the base of the scarp is a small rift or trench (Fig. 5) evidently not cut by a stream. The scarp continues southward along the foot of the mountains to Sheep Creek, about 1½ miles,

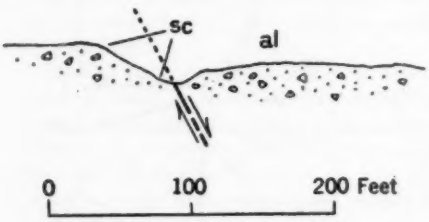

FIGURE 5.—FAULT RIFT; CROSS PROFILE
al. alluvium sc. Recent scarp

and, where it crosses an alluvial fan, it is nearly 40 feet high. Beyond Sheep Creek it follows the edge of the alluvium and talus at the base of the mountains to Slide Creek, a distance of about 2 miles, where it becomes irregular and indistinct. Beyond Slide Creek the mountain-front segment is faulted a mile or more farther west, and the scarp reappears above the alluvium as the lower part of a scarlike band 100 feet or more high formed of bare rock faces inclined 45°–50°. A little farther on at Little Mile Creek below "Montbestos", the mine of the United Asbestos Co., the scarp, here about 10 feet high, crosses an alluvial fan and continuing southward dies out in the canyon of Mile Creek.

Going northward from the Madison River the Recent scarp hugs the foot of the range for 15 miles or more. At the beginning of this stretch the scarp beheads alluvial cones and crosses glacial moraines. Farther on its detailed course is somewhat irregular with local splits or branches, and its height differs from place to place but averages 20 feet or more. For a distance beyond Wolf Creek the scarp becomes indistinct, and the mountain front is faulted to a position 3 or 4 miles to the right (east). Thence northward the succeeding section of the scarp reappears along the South fork of Indian Creek where it cuts a deposit of glacial outwash. At Indian Creek the scarp crosses a nearly level alluvial plain which is relatively downthrown about 15 feet toward the basin. North of Indian Creek it appears plainly for about 2 miles but farther on becomes broken and indistinct around the spur south of Bear Creek.

At Bear Creek the mountain front again recedes eastward, and from that stream to Cedar Creek, a distance of 10 miles, the scarp is distinct though less striking. Near Mill Creek a branch splits off and extends northeastward across that stream and disappears up the mountain slope beyond. North of Mill Creek the scarp, as seen from a distance, becomes a fairly distinct scar band 50 feet or more high on the mountain slope below the edge of the timber. Near Cedar Creek it coincides with notches that cross projecting spurs of Madison limestone. Beyond the stream it reappears in alluvial deposits at the base of the mountain front and continues to Jack Creek, gradually becoming less distinct. On the spur south of Jack Creek the scarp falls approximately in line with the lower part of a rock face rising with a 25- to 30-degree slope from a terrace plain to a small shelf about 200 feet above. North of Jack Creek the Recent scarp was not definitely identified.

Above the Recent scarp the general front slope of Madison Range looks like a maturely dissected fault scarp. The slope rises abruptly and steeply 2000 feet or more to a general crest at about 9000 feet altitude surmounted by peaks 1000 to 2000 feet higher (The Wedge, 10,840 feet: Mt. Taylor 11,251 feet.) It is drained by perpendicular streams of steep gradient with rapids along their lower courses. The streams are confined to narrow or V-shaped valleys not adjusted to the rock structures and not noticeably widened at their mouths. Most of the smaller streams enter the basin above alluvial fans or cones. The truncated ends of interstream spurs are as much as 2000 feet high.

An eastward 5- to 10-degree tilting of the fault block beneath Madison basin is indicated by the slope of the peneplain as preserved on spur backs and the rhyolite sheet on the east side of Gravelly Range. As determined by projecting the profile of this slope to the fault the displacement of the peneplain is 4000–5000 feet vertically, equivalent to a downthrow of 6000 feet or more, assuming the dip of the fault plane to be 45° (Pl. 5, I).

The displacement was greatest along the

middle and southern parts of the basin and continued southward through Reynolds Pass and for a distance along the basin of Henry's Lake. Northward it seems to have decreased and died out as the fault turned westward around the end of the basin or gave place to another along the valley of North Meadow Creek (Fig. 4). In the middle and southern parts of the basin the position of the river at the western side of the basin, together with the position of the rapids in the streams and in the river just above the fault line, suggests an elevation of the range block by later movements.

The Recent fault scarp at the base of the Madison Range, though not quite so fresh looking, is similar to the Recent fault scarps at the base of the Wasatch Range (Gilbert, 1890, p. 340–350) and in the Great Basin region (Russell, 1885, p. 274–283). It is not noticeably modified by weathering. Rapids in Madison River have retreated but a short distance above the fault line and in Indian Creek hardly at all. The scarp is covered by grass and shrubs and in places scattered trees. The oldest tree observed on the scarp was represented by a fir stump near the top of the scarp slope just south of Madison River. The stump, seen in 1936, contained 150 annular rings. It is judged that the scarp has existed in its present form since about 1770.

The total displacement estimated for this fault is probably the sum of many small movements that, as required by the mature dissection of the older scarp, probably began in late Tertiary time.

Cliff Lake fault.—Cliff Lake at the southwest of Madison basin (Pl. 1, No. 47) is in a trenchlike depression along a fault that displaces the Late Tertiary peneplain on an area of rhyolite lava. The fault, as indicated by the alignment of the trench with the valleys of the West Fork and Madison rivers, continues northward for 12 or 15 miles. Southward a segment of the fault is offset to the west and is traced by ponded rifts and trenches through Hidden Lake Pass to the edge of Centennial basin (Pl. 1, No. 51). Including this segment the length of the fault is about 25 miles.

The rhyolite underlies the east and southeast slopes of the southern part of Gravelly Range. It extends south to the edge of Centennial basin, southeastward across Hidden Lake Pass, and eastward to the edge of Madison basin. As exposed in the valleys of streams that drain the mountain slope, the lava is from 100 to several hundred feet thick and overlies pre-Tertiary rocks. At the edge of Madison basin it passes over Tertiary "lake beds."

A fairly even erosional surface developed over most of the rhyolite area slopes from an altitude of 9000 feet at the top of Gravelly Range to somewhat less than 7000 feet at the edge of Madison basin. This surface is correlated here with the Late Tertiary peneplain. It is partly dissected by narrow stream valleys and near the basinward margin gives place to low hills of pre-Tertiary rocks.

The most interesting features of the rhyolite area are riftlike depressions that hold Cliff Lake and several smaller lakes, most of which have no visible outlets. Cliff Lake is about 3 miles long from north to south, less than a quarter of a mile wide, and at the south is separated into four small fingers. The main part of the trench is aligned with the valleys of West Fork and Madison rivers to the north. It receives three small streams, one of them draining the extreme southern part of Madison basin. The lake has no visible outlet; it probably drains through loose materials beneath the lava sheet (Mansfield, 1911, pp. 54–63) or beneath landslides that block the trench farther north. The altitude of the lake is about 6500 feet or some 500 feet higher than the West Fork and the Madison rivers. Slopes formed of hummocky landslides and precipitous lava cliffs rise from the water's edge to the lava surface about 600 feet above. Owing to the presence beneath the lava of loosely consolidated Tertiary "lake beds" that dip eastward, most of the landslides are on the western side of the lake (Fig. 6).

A short distance north of Cliff Lake the trench holds Wade Lake; 3 miles beyond Wade Lake the trench is continued by the valleys of the West Fork and Madison rivers which form a narrow depression 8 or 10 miles.

Only general observations were made of the trench in Hidden Lake Pass. It lies across a divide and holds Hidden Lake, Elk Lake, and two or three small ponds. It trends south-southwest, is concave to the west, and is offset from Cliff Lake trench about 2 miles to

the west. Looking north from Centennial basin it marks a westward downthrow of the lava surface.

Along the Cliff Lake trench the rhyolite surface appears to be downthrown 200 feet or

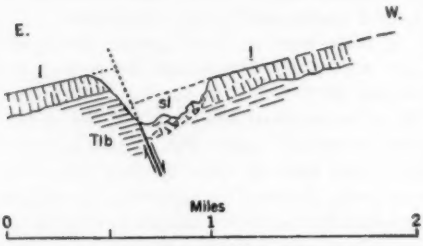

FIGURE 6.—CLIFF LAKE TRENCH; CROSS PROFILE
l. lava
Tlb. Tertiary "lake beds"
sl. slide

more toward the west (Fig. 6), and there is a similar displacement along the lower West Fork Valley and the narrow valley of Madison River beyond.

The faulting that formed the trench is probably middle or late Pleistocene. If earlier, the trench should be more extensively waste-filled and its walls less prominent or less well preserved.

For 10 or 12 miles mostly along the Madison River and partly along the West Fork, the streams in the southern part of Madison basin are intrenched in the side of the Gravelly Range at right angles to the slope. To reach this position the Madison River crosses the axis of the basin and passes between foothills at the west. North of the river Wolf Creek takes a similar course and enters a gorge cut into the rising surface. The stream that drains the extreme southern part of the basin enters Cliff Lake in the same way. These relations might be explained as the effect of glaciers that descended from the Madison Range, filled the basin, and crowded the drainage. If the fault rift had existed it would, of course, have carried the drainage and, if deepened by erosion or continued faulting, would have continued to hold the stream after the ice had melted. Moraines indicate that later glaciers descending Wolf Creek and other streams reached at least part way across the basin. A coarse wash exposed (Fig. 3) on top of the slope east of the river a short distance below the mouth of the West Fork may be the deposit of an earlier large glacier that crowded the drainage. This deposit contains angular masses of gneissoid rocks up to 10 feet in diameter from the Madison Range.

Centennial fault.—The bold north front of the Centennial Range (Pl. 4, fig. 1) is interpreted as the worn scarp of a fault that has elevated the range and tilted it gently southward. This idea is supported by the attitude and relations of the rocks and by evidence of renewed movement on the fault in late Pleistocene or Recent time.

From a gap in the south rim of Henry's Lake basin (Pl. 1, No. 50) the Centennial Range extends westward to a gap at Monida forming, except at the extreme east, the Continental Divide and the Montana-Idaho boundary. In this stretch of about 45 miles the abrupt north front of the range faces a chain of depressions formed by Centennial valley (Pl. 1, No. 51), Alaska basin, Red Rock Pass, and Henry's Lake basin from west to east (Fig. 7). In the eastern and higher part of the range the main summits reach heights of as much as 3500 feet above the adjacent depressions or a maximum altitude of about 10,000 feet. Intervening gaps are 1000 to 2000 feet lower. The rocks forming this part of the range are mostly Mesozoic and older sandstones and limestones (Condit, *et al.*, 1928, p. 206–209) that dip 20°–30° S. (Fig. 7, sec. AA'). Unconformably above these on some of the summits are Tertiary rhyolitic and basaltic lavas, remnants of beds that dip less steeply in the same direction. Westward, the range crest becomes more nearly uniform and almost entirely underlain by the lava beds. Beyond Odell Creek the lava beds deepen and from Jones Creek on are the only rocks exposed in the front slope. The range crest descends gradually westward to about 8000 feet near Moniea. The long back (south) slope formed mostly of the lava beds descends gently to the Snake River Plain.

The floor of Centennial Valley is a nearly level plain, and the drainage is sluggish and ponded. At the lower (west) end of the valley the current of Red Rock Creek becomes slightly accelerated. There the stream has been ponded artificially in the Lima Reservoir.

The mountains north of Centennial valley rise gradually from an irregular base line winding in and out around spurs from the south ends of the Gravelly and Snowcrest ranges. The slopes are chiefly southward-dipping lava beds, apparently the same as those on the Centennial Range opposite.

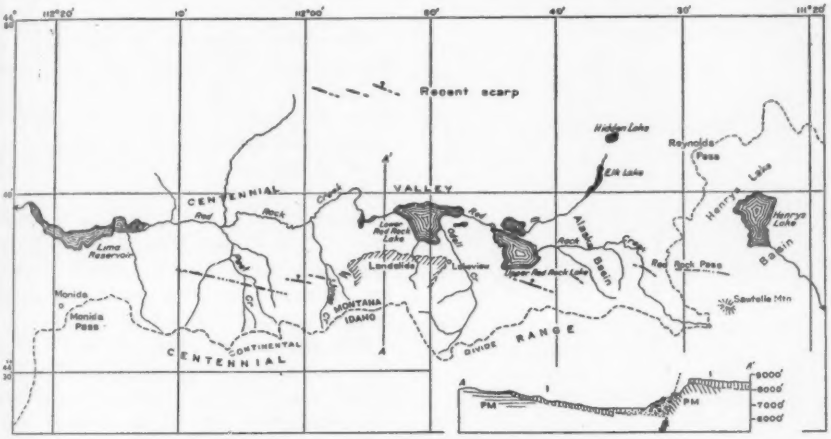

FIGURE 7.—CENTENNIAL FAULT; PLAN OF RECENT SCARP
l. lava PM. Paleozoic and Mesozoic beds

The floor of Alaska basin is a small alluvial plain slightly higher than Centennial valley. Red Rock Pass is a wide low gap crossing the Continental Divide to Henry's Lake basin. The northern sides of both the Pass and Alaska basin are much lower and rise less abruptly than the front of Centennial Range. Henry's Lake basin is a nearly circular depression about 10 miles across. Its outlet gap at the southeast opens on a plain, formed by a lava flow of probable post-Tertiary age, that extends southward along the Yellowstone Park plateau and ends in an escarpment descending to the Snake River Plain near Ashton, Idaho. On the west of Henry's Lake basin is an unnamed range of moderate height, and on the northest and east the basin is enclosed by an extension of the Madison Range beyond Reynolds Pass and farther on by the Targhee Range, both presenting rather abrupt and regular fronts suggestive of worn fault scarps.

The fault indicated by the front of Centennial Range is definitely traced in places by a low scarp (Fig. 7) formed in unconsolidated deposits along the base of the slope. The scarp faces the lowlands, slopes at the angle of repose for loose materials (30°–33°), and is broken into segments arranged en echelon. Eastward in Centennial Valley the scarp is first seen a short distance south of the road at a point about 9 miles from Monida where it appears as a low terrace crossing an alluvial plain at the mouth of a small valley. Its course is about S. 75° E., and its height 10 feet or less. In the next 8 or 10 miles it displaces several other small plains and, along intervening stretches, is aligned with truncated spur ends, lines of springs, and patches of "slump" topography. About 3 miles beyond Peet Creek the scarp gives place to a notch in a small spur of basaltic lava. Farther on in the alluvial plain of Jones Creek it reappears and becomes separated into two slightly diverging branches. A short distance beyond it is buried under a huge land slide extending along the range front for 6 or 7 miles.

At Lakeview the mountain front recedes southward along Odell Creek. The scarp was not observed on the extensive alluvial plain of that stream, but farther east another segment appears on a plain southeast of upper Red Rock Lake; it is 6 to 10 feet high and trends about S. 75° E. Farther on it passes into a notch in a small glacial moraine. Whether it continues

in the timbered area beyond was not determined.

In Alaska basin another segment of the scarp cuts off the lower part of an alluvial fan at the mouth of Red Rock Canyon. There its course

FIGURE 8.—RED ROCK FAULT; PLAN OF RECENT SCARP

is S. 70°–80° E., and its height about 15 feet. Westward, this course falls in line with some north-facing spur ends. On the east the scarp turns somewhat southward, crosses an alluvial cone, and dies out along a trench extending obliquely up the steep and rocky mountain front.

In Henry's Lake basin two projecting rock spurs and several moraines of glaciers from the Centennial Range (W. C. Alden, personal communication) are either notched or cut off on the north as if by faulting along a course of about S. 85° E. in line with Red Rock Pass.

In places for a distance of 30 miles or more along the base of the Centennial Range displacement of 10 to 20 feet is measured by the scarp of late Pleistocene or Recent age. Actual depression of the valley block is indicated by sluggish drainage and ponds near the fault line.

The mature dissection of the fault scarp represented by the north front of Centennial Range, including the effects of glaciation, indicates exposure since at least the middle Pleistocene. Near Lower Red Rock Lake a downthrow of 2000 feet or more toward the north is indicated by the relative positions of the lava surface at opposite sides of the valley (Fig. 7, AA′). In Red Rock Pass and Henry's Lake basin similar geologic criteria are lacking, but the height of the mountain front suggests an uplift of 3000 feet or more.

Red Rock (Lima) fault.—A fault (Fig. 8) that has relatively downthrown Red Rock (Lima) valley is traced by a Recent scarp at the northeastern base of the Tendoy Mountains.

Red Rock or Lima Valley (Pl. 1, No. 52), a basinlike depression along the northeast side of a prominent range known as the Tendoy Mountains, is about 35 miles long, 5 or 6 miles wide in the middle, and connected by narrows with Medicine Lodge Valley on the northwest and Centennial Valley on the southeast.

The Tendoy Mountains present an abrupt and regular front (Pl. 3, fig. 2) rather deeply scored by perpendicular streams. Opposite Dell these mountains are cut through by the narrow gorgelike valley of Sheep Creek which drains a large area beyond. The mountains are composed chiefly of steeply tilted Mesozoic and older rocks. In the northwestern part of the

PLATE 2.—LATE TERTIARY PENEPLAIN AND OLD VALLEY REMNANTS

FIGURE 1.—PENEPLAIN ON THE SAPPHIRE MOUNTAINS

West of Willow Creek-Rock Creek Trench.

FIGURE 2.—VIPOND PARK, REMNANT OF AN OLD VALLEY ON THE PIONEER MOUNTAINS

FIGURE 3.—PRIEST PASS, REMNANT OF AN OLD VALLEY ON CONTINENTAL DIVIDE

West of Helena.

PLATE 3.—RECENT SCARPS

FIGURE 1.—RECENT SCARP AT BASE OF MADISON RANGE

In background, Upper Madison Canyon, the entrance gorge of Madison River.

FIGURE 2.—RECENT SCARP OF THE RED ROCK FAULT AT BASE OF TENDOY MOUNTAINS

Spur-end facets above represent the older scarp.

FIGURE 3.—RECENT SCARP OF THE RED ROCK FAULT ACROSS ALLUVIAL PLAIN

At mouth of Sheep Creek.

FIGURE 1

FIGURE 2

FIGURE 3

LATE TERTIARY PENEPLAIN AND OLD VALLEY REMNANTS

FIGURE 1

FIGURE 2

FIGURE 3

RECENT SCARPS

FIGURE 1

RAMPART MOUNTAIN ELK PARK EAST RIDGE

FIGURE 2

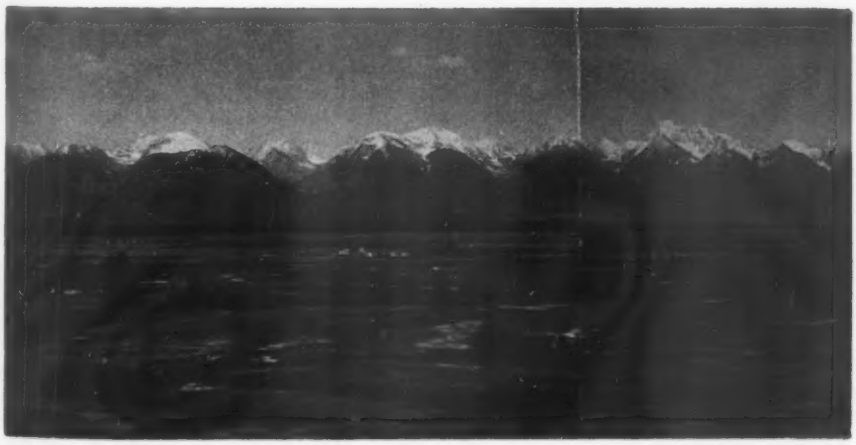

FIGURE 3

OLDER SCARPS

Tendoy Mountains the rocks strike about parallel to the mountain front but dip away from it. To the southeast beyond Dry Canyon, the mountain front crosses the structures obliquely.

The opposite (northeast) side of the basin is a gradual slope of less definite and regular outline. It is formed chiefly of gravel or conglomerate beds and volcanic rocks, all presumably Tertiary. The conglomerates extend down into the valley and pass beneath the alluvial fill. Red Rock is a projecting ledge of reddish-brown sandstone, probably Triassic, that dips 35° E.

From a point west of Sheep Creek southeastward 10 miles or more to the head of the valley near Lima a Recent fault scarp is visible along the base of the mountain front (Pl. 3, fig. 2). It faces the valley, cuts alluvial cones, and slopes at about the angle of repose for loose material (30°–33°). Above it are several triangular spur-end facets. At the mouth of Sheep Creek Canyon the scarp (Pl. 3, fig. 3) is about 20 feet high. Southeastward its height decreases to about 15 feet at Chute Canyon and about 10 feet at Little Sheep Creek opposite Lima. Just west of Little Sheep Creek a south branch splits off (Fig. 8) and extends for a short distance with a more southerly course across the stream and up a gulch opposite. Continuing southeastward the main scarp again splits. One branch disappears up the gulch back of a lava-capped hill. The other curves eastward around the head of Red Rock Valley and dies out within a couple of miles.

Back of the Recent scarp the end slopes of several truncated mountain spurs rise somewhat more steeply to heights of several hundred feet. West of Sheep Creek several of these spurs are notched back of the facets.

A relative downthrow of 6 to 20 feet toward the valley is measured by the Recent scarp, and several hundred feet additional displacement is indicated by the spur facets above. If, as seems probable, the entire mountain front is a badly worn fault scarp the maximum displacement may be as much as 3000 feet. The movements began in the Pliocene or earlier.

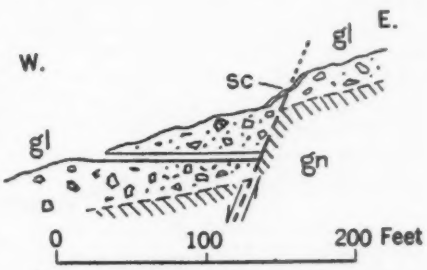

FIGURE 9.—EMIGRANT FAULT; SECTION AT D'EWART'S RANCH, YELLOWSTONE VALLEY

gl. glacial drift
gn. gneiss
sc. fault scarp

Emigrant fault.—Physiographic evidence, including a (Recent?) fault scarp, indicates that the valley of the Yellowstone River from the narrows above Livingston to Yankee Jim Canyon, about 35 miles farther south has been relatively depressed along a fracture, called the Emigrant fault, at the base of the steeply rising mountain front of (Pl. 5, D). The trace of the fault passes through or near the site of Emigrant, a former mining camp (not the present Emigrant, a station on the Northern Pacific Railway). The name Emigrant is also applied to the basin to distinguish it from other parts of the valley of the Yellowstone River.

Emigrant basin (Pl. 1, No. 48), a well-defined intermontane basin between the Snowy Range (Beartooth plateau) on the east and the Gallatin Range on the west, is about 35 miles long (N. 30° E.) and 6 miles wide near the middle. Its floor, 4600 to 5600 feet in altitude, is alluvial lowland plains, moderately elevated

PLATE 4.—OLDER SCARPS

FIGURE 1.—OLDER SCARP OF CENTENNIAL FAULT REPRESENTED BY ALIGNED BLUNT SPUR ENDS
Rising abruptly from alluvial plain of Henry's Lake Valley.

FIGURE 2.—SCARP OF CONTINENTAL FAULT
Formed by abruptly rising slopes of Rampart Mountain (left) and East Ridge (right). Detached foothills below East Ridge form scarps of smaller movements on parallel planes of the fault zone. Branch of main fault turns into Elk Park Valley back of Rampart Mountain.

FIGURE 3.—SCARP OF MISSION FAULT
Formed by the abruptly rising front of the Mission Range.

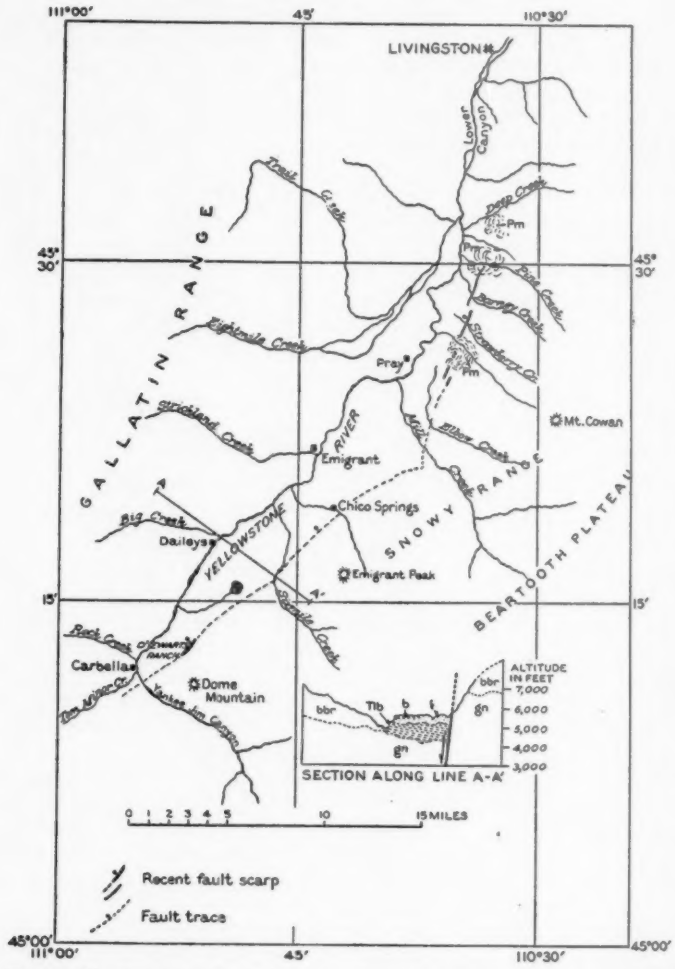

FIGURE 10.—EMIGRANT FAULT; PLAN OF LATE PLEISTOCENE OR RECENT SCARP

terraces plains or benchlands, and irregular surfaces characteristic of glacial deposits. In the southern part between Point of Rocks and Dailey's, an escarpment 300 feet high east of the river exposes Tertiary "lake beds," chiefly impure volcanic ash, that dip 10°–20° E. Above the ash beds is a layer of gravel and upon that a flow of basalt, which in turn is overlain by glacial drift (Fig. 10, AA').

Except for the gorges through which the Yellowstone River enters and leaves at the north and south respectively, the mountainous rim of Emigrant Valley is unbroken although toward the northwest it is lowered somewhat by the pass at the head of Trail Creek. The Snowy Range along the east is part of the extensive Beartooth Plateau, a partly dissected upland at an altitude of 10,000 to 12,000 feet. Along Emigrant basin the elevated mass presents an imposing front 4000–5000 feet high. It has a fairly simple outline and is drained by streams of steep gradient whose valleys, except where widened by glaciation, are narrow and gorgelike. The profile of the front is steep

throughout and in places somewhat oversteepened near the base.

The front of the Beartooth plateau facing Emigrant Valley is chiefly Precambrian gneiss and schist (Iddings and Weed, 1894). Toward the north these give place to steeply tilted Cambrian to Cretaceous limestone and other rocks. South of Mill Creek another area of Paleozoic rocks forms from the lower part of the mountain front, and Miocene volcanics underlie part of the upland.

Gallatin Range on the opposite (west) side of the basin rises less steeply to a general summit level of 9000–10,000 feet. It is drained by streams of moderate gradient in valleys that widen somewhat toward their mouths. Areas of flat or gently sloping surfaces form parts of the summit and descend short distances on some of the spurs. The range is underlain by Miocene volcanic rocks except at the north where deformed Paleozoic and Mesozoic sedimentary beds appear from beneath the igneous cover. The volcanics descend to the valley and pass beneath the alluvial fill. In recent years many additional stratigraphic and structural details of the valley and adjacent areas have been worked out (Lammers, 1937; Skeels, 1939.

After a study of the physiographic problems Horberg (1940) concluded that a relative down throw of at least 5000 feet toward the basin has occurred on a fault along the base of the Beartooth Range on the east. Stratigraphic evidence of the displacement is found along the North Snowy block—namely, that part of the elevated mass north of Mill Creek. Along the South Snowy block beyond Mill Creek the faulting, as pointed out by Horberg, is indicated by topographic features such as the abruptness and continuity of the mountain front, truncated spurs, hanging valleys, the absence of foothills, a linear scarp near the base of the range, and a marked difference in elevation between certain areas of volcanic rocks (early basic breccias) in the Beartooth Range and in the Gallatin Range to the west.

A feature significant of the faulting was observed by Gail (1937, p. 16) who describes it as a "possible young fault scarp which cuts an alluvial fan". The locality given is southeast of the highway about 2 miles below the mouth of Yankee Jim Canyon. Here a scarp in the form of a moderately steep slope 7 or 8 feet high cuts across an alluvial fan or cone at the base of Dome Mountain. It continues about N. 35° E. (Fig. 10) regardless of changes in the land form and may be identified for at least a mile. In places springs rise along it, and an excavation to develop one of them on D'Ewarts ranch exposes the fault at a depth of 20 feet. Here the fault cuts glacial drift (Fig. 9) and passes into the bedrock beneath; it dips about 50° W. Northward from this locality to Mill Creek the scarp has not been traced, but its projected course lies along the foot of the mountain slope and about in line with Chico Hot Springs.

In the northern part of the basin a similar scarp may be traced with interruptions for 5–6 miles from a point about 2 miles north of Mill Creek to Pine Creek. It parallels the base of the mountains, lies a few hundred feet out from it, is 8 or 10 feet high, and maintains a regular course despite changes in slope and form of the general surface. At Barney Creek the scarp crosses a meadow and continues up a slope beyond underlain by older glacial drift and outwash from Pine Creek. It was not, however, observed to cross a newer moraine.

Evidently the slight movement that produced the low scarp was in late Pleistocene or Recent time. The greater movement represented by the scarplike eastern mountain front is, of course, much older. Evidence indicates (Horberg, 1940, p. 293) that the development of the basin began in the Miocene with faulting and warping that continued intermittently up to Recent time.

Bridger fault.—A fault that has elevated the Bridger Range is suggested by the regular course, abrupt rise from Three Forks basin, and other scarplike features of the mountain front.

Three Forks basin, one of the largest intermontane depressions, occupies more than 1000 square miles that includes the lower valleys of the Gallatin, Madison, and Jefferson rivers (Pl. 1, No. 33). Its general outline approaches that of a rectangle 40 miles long from east to west and 25 miles wide, but in detail it is irregular because of several projecting arms one of which, the valley of Dry Creek at the northeast corner), is 4–5 miles wide and 10 miles long.

The basin rim is formed by mountain ranges

that in places rise to peaks 5000–6000 feet high and, in places opposite Townsend basin on the north and Madison basin on the south, descend to wide low ridges. South of Jefferson

FIGURE 11.—WEST FRONT OF BRIDGER RANGE; SPUR END FACETS

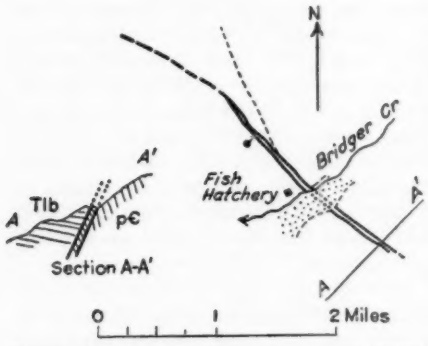

FIGURE 12.—PLAN OF DOUBLE SCARP OF FAULT AT BASE OF BRIDGER RANGE

Tlb. Tertiary "lake beds"
pC. Precambrian rocks

Canyon the rim is lowered by a broad wind gap leading to the Beaverhead-Jefferson basin. Another gap extends from the head of the Dry Creek arm to the valley of Sixteen Mile Creek. The Gallatin, Madison, and Jefferson rivers enter from gorges at the southeast, south, and northwest (Jefferson Canyon) respectively and, united as the Missouri River, escape through a gorge at the north.

The basin floor, 4100–5600 feet altitude, is largely alluvial plains (Pl. 5, F, G, H) that slope inward and northward. They include wide lowlands along the main streams and extensive terraces at different heights, one at the south along the Madison River is 1000 feet above the stream. Exposures in terrace escarpments indicate that the Tertiary "lake beds" extend beneath the gravel cover throughout most of the basin.

Bridger Range (Pl. 1) extends from the head of the Dry Creek arm along the east side of Three Forks basin for about 25 miles to a gorge (Bridger Canyon) along Bridger Creek, a stream entering from the east near the southern limit of the basin. The range rises abruptly and steeply about 3000 feet from a terrace plain to a narrow but rather smooth and even summit at about 8500 feet altitude (Pl. 5, C) with here and there a peak a few hundred to a thousand feet higher (Sacajawea 9500 A. T.) It is formed of Mesozoic and older rocks that strike northwest parallel to the mountain axis and are steeply inclined, in places standing vertically or overturned to the east. The front slope presents a slightly convex profile with perpendicular drainage lines not adjusted to the structure. Spur ends are blunt and in the section between Cottonwood Creek and Ross Creek are faceted (Fig. 11); the bases of the facets are aligned. There are no foothills. The base line is separated by offsets into several segments or sections that trend N. 20° W. to N. 30° W.; the average, including offsets, is about N. 15° W. From the Fish Hatchery at the mouth of Bridger Canyon a double escarpment as much as 100 feet high extends a mile or more northwestward (Fig. 12) along the base of the range and, in places, crosses the rock structures. Projected southeastward across Bridger Creek its course passes up a ravine and coincides with two small notches in the crest of a ridge.

To the west opposite the northern part of Bridger Range, the Horseshoe Hills formed of the same rocks rise gradually about 1000 feet from an irregular base line to a wide smoothly rounded general summit with a peak a few hundred feet higher. The slope is somewhat concave upward, and its spurs carry the smooth upland surface down part way to the basin floor.

As exposed south of Bridger Creek, the Tertiary lake beds dip toward the range. This fact and the scarplike mountain front indicate that the en echelon base line is the trace of a fault that has elevated the range.

No movement has occurred since the narrow alluvial plain of Bridger Creek was formed. On the other hand, the preservation of the spur-end facets indicates that much of the displacement is not older than Pleistocene. Interpreting the general summits of Bridger Range and

Horseshoe Hills as dislocated parts of the Late Tertiary peneplain, the total relative downthrow is 3000 feet or more.

Fault east of Clarkston basin.—The rather severe earthquake of June 27, 1925, is thought to have been caused by renewed movements on a fault along the east side of Clarkston basin. Although no definite scarp was formed, ground cracks were opened by the shaking (Pardee, 1926, p. 20–22) along a line interpreted as the probable trace of the fault. An early westward downthrow along this fault is indicated by an eastward dip of the Tertiary "lake beds."

Clarkston basin (Pl. 1, No. 32) is a small intermontane depression along the Missouri River between Three Forks basin on the south and Townsend basin on the north. Clarkston, altitude 4002 feet, a station on the Northern Pacific Railway, is on the river at the west side of the basin.

Hills and mountains surround the basin and, except for the inlet and outlet gorges of the Missouri River, form an unbroken rim of pre-Tertiary rocks. On the east the Horseshoe Hills present a moderately steep rather uneven slope rising from a fairly regular base line a little back of the indicated trace of the fault to rounded summits 2000 feet or more high. The slope crosses folded beds in a direction oblique to the general northeastward trend of the structures.

Horseshoe bends in the gorges of the Missouri River north and south of the basin, particularly at the north (Pl. 1), are evidently meanders intrenched below a former position of the stream. A northward-descending surface on which the river established the meandering course is probably represented by flat and gently sloping summits about 600 feet high on the rim west and northwest of the basin. These features fall in place with the profile of a high terrace (No. 1 bench, Pl. 5, F) projected from Three Forks basin at the south. The terrace is of early or middle Pleistocene age.

Except for the cracks opened by the earthquake no evidence of faulting later than bench No. 1 was observed. The downthrow, as indicated by the relation of the Tertiary "lake beds" to the older rocks (Fig. 13), was at least several hundred feet.

Faults east of Townsend Valley.—In places the mountain front along the east side of Townsend Valley rises abruptly and otherwise exhibits features of a worn fault scarp. On Six Mile Creek east of Toston, definite evidence of a fault with a downthrow toward

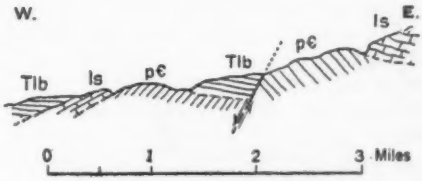

FIGURE 13.—CLARKSTON FAULT; CROSS SECTION
Tlb. Tertiary "lake beds"
ls. limestone
p.€ Precambrian rocks

the valley appears at the base of the slope.

Townsend Valley (Pl. 1, No. 30) along the Missouri River southeast of Helena is an intermontane basin 5–15 miles wide and about 40 miles long including a wide embayment along Crow Creek at the southwest.

At the north the Spokane Hills and the Belt Mountains close around the basin except for a gorgelike narrows through which the Missouri River escapes. On the south the Elkhorn Range descends to a wide low ridge extending south and east around the Crow Creek embayment to the gorge from which the Missouri River enters Townsend basin from the neighboring Clarkston basin. Beyond (east of) the gorge a spur south of Six Mile Creek projects westward from the Belt Mountains completing the south rim. Along the east the Belt Mountains form a moderately high and unbroken rim.

In places the main divides and principal spurs of the mountains that enclose the valley, in particular the northern part of the Belt Range, have wide flats or gently sloping areas, interpreted as remnants of the late Tertiary peneplain. These surfaces descend from about 7000 feet on the main divides to 6000 feet or less on the principal spurs.

Fault scarps are strongly suggested by parts of the eastern mountain front along the southern part of the basin between Deep Creek and Six Mile Creek and along the northern part beyond Confederate Creek. Between Six Mile Creek and Deep Creek about 8 miles to the

north the mountain front rises along a course of about N. 15° W. rather steeply and abruptly to a height of 1000 to 2000 feet. Back of this slope the spurs ascend more gradually an additional 1000 feet to a broad summit of about

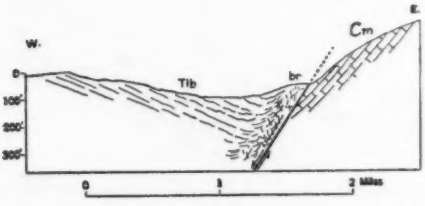

FIGURE 14.—FAULT AT SIXMILE CREEK; CROSS SECTION
Tlb. Tertiary "lake beds"
Cm. Madison limestone
br. fault breccia

7000 feet in altitude. From Deep Creek north to Confederate Creek, a distance of about 20 miles, the mountain base line is irregular and receded eastward 3 or 4 miles from its position farther south. In this section the mountains appear old; the slopes are smooth. From Confederate Creek to the northern end of the basin, however, the range front, advanced somewhat from its course to the south, rises abruptly with truncated spur ends 1000 to 2000 feet high, aligned along their bases in a northwestward course concave to the basin.

At the south between Six Mile Creek and Deep Creek, spurs from the Belt Mountains end along a regular line that trends about N. 20° W. and forms the boundary between the older rocks and the Tertiary. Where Sixmile Creek crosses this line, a coarse breccia is exposed next to a fault plane that dips 60° toward the valley (Fig. 14). The hanging wall is composed of sand, clay, and gravel of the Tertiary "lake beds" that dip 20°–30° E. or toward the fault plane. Here an exposed thickness of about 500 feet of the Tertiary beds is in fault contact with Paleozoic rocks (Quadrant formation and Madison limestone). For a few miles north of Sixmile Creek the fault is traced by a slight depression along the base of the mountain front. Out in the valley small normal displacements in the "lake beds" have occurred on faults parallel in direction and dip to the one at Sixmile Creek (Pardee, 1925, p. 16, Fig. 4, p. 32).

Between Deep Creek and Confederate Creek the boundary of the Tertiary is somewhat out from the base of the slope, and the gently ascending benchland surface continues eastward for a short distance across the older rocks.

From Confederate Creek to the north end of the basin the mountain front parallels the rock structure in places and in places crosses it. The Tertiary beds in this part of the basin are largely concealed by alluvium, but in exposures at Cave Creek and Magpie Creek the beds are flexed upward at the base of the mountains, an effect presumably of "drag" on the fault.

A minimum downthrow of 500 feet toward the basin is indicated at Six Mile Creek, and the height of the spur facets suggests at least that much additional. North of Confederate Creek the height of spur facets and the altitude of near-by remnants of the peneplain indicate a downthrow of about 2000 feet. No evidence was observed to fix the age of the faulting more closely than post-Miocene.

Faults in Prickly Pear basin.—The series of strong earthquake shocks at Helena in October 1935 was probably caused (Scott, 1936, p. 23–25) by renewed movements on a fault along the southwestern side of the Prickly Pear basin (Pl. 1, No. 21). Instrumental records and the surface effects of the shocks indicate that the locus of the earthquake is deep-seated, and the epicenter a short distance north of Helena. At the western side of the basin a fault is indicated by the scarplike front of the Scratch Gravel Hills, but no superficial evidence of renewed movement on the fault as an effect of the earthquake was observed.

Prickly Pear basin is an intermontane depression about 20 miles long and 10 or 12 miles wide. The basin floor, 3700–4200 feet in altitude, is formed of alluvial plains that, in the western half of the basin, merge into a wide flat in front of the Scratch Gravel Hills. The alluvial deposit underlying the flat may be more than 1200 feet deep (Knopf, 1913, p. 94). The eastern half of the basin is occupied chiefly by a graveled terrace rising gradually to the Spokane Hills from an escarpment 100 to 150 feet high. The gravel cover rests on a surface eroded across Oligocene and Miocene sedimentary beds which in turn overlie strongly deformed pre-Tertiary rocks. Prickly Pear

Creek enters from the southeast, turns northwestward across the flat, thence eastward, and, before it became ponded as Lake Helena—an artificial reservoir—finally reached the Missouri River through a gorge. Streams from the mountains on the southwest and west join Prickly Pear Creek in its course through the basin.

The steep north end of the Elkhorn Range rises at the southeast of Prickly Pear basin to a height of 4000 feet or more. East of the range a wide low pass leads southeastward into Townsend basin, and east of the pass the Spokane Hills extend northward part way along the east side of Prickly Pear basin. North of the Spokane Hills, a wide gap opens to the valley of the Missouri River. In the short distance between this gap and the outlet gorge, the basin rim is a hill a few hundred feet high; the Missouri River is intrenched in a gorge back of it.

North of Prickly Pear basin a low unnamed range rises gradually from an uneven base line. On the west the Scratch Gravel Hills project into the basin between an arm extending up Sevenmile Creek on the south and a wide low gap leading to Silver basin on the north. Toward Prickly Pear basin the hills present a regular front formed by Scratch Gravel Peak, 1300 feet high, and a low south spur.

West of the Elkhorn Range, and separated from it by the narrow valley of Prickly Pear Creek, is a broad upland with the general form of a maturely dissected plateau. Toward Prickly Pear basin, the upland presents a steep north front 2000 feet or more high.

A fault at the south side of Prickly Pear basin is indicated by the mountain front directly back of Helena which, in a general view, suggests a worn fault scarp. For 7 or 8 miles between Holmes Creek and Fort Harrison, the spur ends are blunt and their bases aligned about N. 70° W. oblique to the rock structures.

A fault at the west side of the basin is evidenced by the regular front of the Scratch Gravel Hills rising steeply and abruptly along a regular course of about N. 20° W. Along the low south spur the front is slightly incised by perpendicular ravines that widen somewhat toward the top. Shallow valleys in the gradually descending back slope are beheaded at the crest. The drainage pattern suggests gradual sinking of the area in front of the Scratch Gravel Hills. The basin receives most of its alluvial deposits from the high mountains on the west and southwest. Under stable conditions these deposits would crowd the drainage toward the east side of the basin. Instead, Prickly Pear Creek after entering at the south makes a wide westward swing toward the Scratch Gravel Hills before turning eastward to the outlet.

As measured by the heights of the scarps the relative downthrows of the faults south of Helena and in front of the Scratch Gravel Hills were on the order of 3000 and 1000 feet respectively. The mature dissection of the scarp indicates that most of the movement on the fault south of Helena had occurred by early or middle Pleistocene time. On the fault in front of the Scratch Gravel Hills, small downward movements continuing into the late Pleistocene are suggested by an uncompleted normal "fill" in that part of the basin.

Hilger fault.—Both physiographic and stratigraphic evidence determine a fault that has relatively downthrown Hilger Valley (Pl. 1, No. 20; Fig. 15) along the north.

Hilger Valley is a trenchlike depression 2–3 miles wide and 12 miles long in a direction about N. 70° W. The Missouri River and Little Prickly Pear Creek, both flowing northward, cross the valley near its east and west ends respectively. Both streams enter and escape in rock gorges cut through the enclosing mountains. The Missouri River gorge is the scenic feature enclosed by vertical white limestone walls named by Lewis and Clark the "Gates of the Rocky Mountains". It now holds an artificial reservoir.

The floor of Hilger valley is formed mostly of gently sloping alluvial fans deposited by streams from the mountains along the north. Toward the eastern and western ends of the valley this surface ends at terrace escarpments descending 100 feet or more to narrow alluvial plains along the Missouri River and Little Prickly Pear Creek. From a low divide about midway in the valley the drainage goes eastward and westward to the streams mentioned.

On the north the valley is enclosed by rugged high mountains formed chiefly of Paleozoic limestones and quartzites, and a mass of Precambrian shale and quartzite overthrust from the southwest (Fig. 15). Toward the north-

east these rocks are overlain by a mass of volcanics with rugged outcrops culminating in a prominent spire known as the Beartooth.

At the south of Hilger valley comparatively low mountains formed of Precambrian sedi-

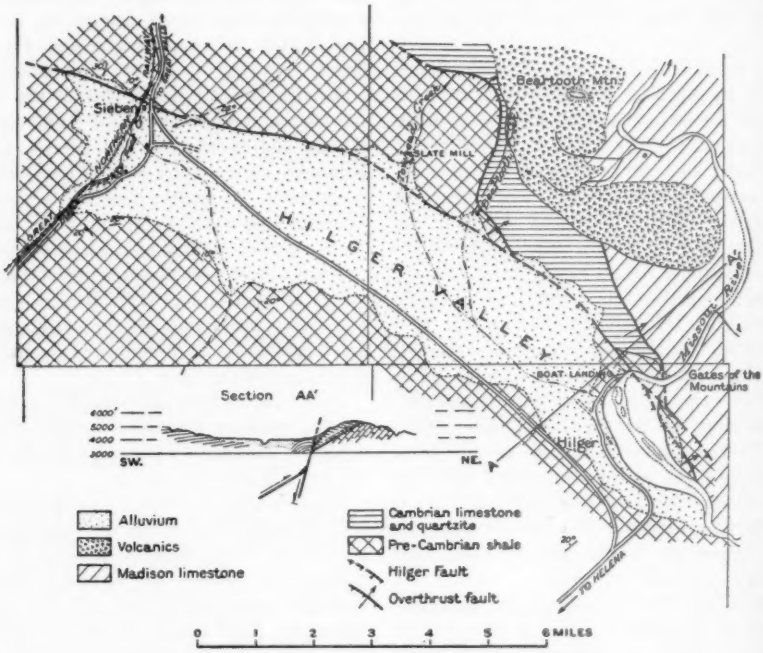

FIGURE 15.—HILGER VALLEY; AREAL GEOLOGY

mentary rocks rise gradually from an irregular outline. On their summit, flat or gently sloping areas occur at 5000–6000 feet altitude. Similar uplands of small extent occur also on the mountains north of Hilger valley at altitudes of 5500–7000 feet. These areas are thought to represent the former surface called the Late Tertiary peneplain.

The mountains along the north present toward the valley a regular and abruptly rising front with truncated spur ends aligned along their bases. For a mile west of Little Prickly Pear Creek the lower 100 feet is oversteepened (Pardee and Schrader, 1933, p. 27) to a slope of 40° that cuts shale of the Belt series dipping 10° N.; the N. 70° W. course of the scarp is also oblique to the strike of the shale. East of Little Prickly Pear Creek the fault is traced by aligned spur ends that are oversteepened below and rise along a regular course. Near the Missouri River the fault cuts and displaces both the main overthrust and a slice (Fig. 15).

The gorges along the Missouri River and Little Prickly Pear Creek are cut below wide upper outer valleys whose floors are represented by spur backs or shoulders 500–600 feet above each stream. In cross profile the sides of the upper outer valleys rise gradually about 1000 feet to the peneplain as represented by the smoothly rounded general summits of the mountains. These elevated old valleys end "up in the air" at the mountain front. As they cross the fault line to enter their respective gorges the Missouri River and Little Prickly Pear Creek pass from alluvial fills onto bedrock, and their currents become accelerated.

The difference of about 600 feet in altitude between the Old Valley and the present valley floors may be taken as the minimum displacement on the Hilger fault. Probably most of it had occurred by early or middle Pleistocene time, but the oversteepened basal part of the scarp west of Little Prickly Pear Creek suggests

a final movement not older than late Pleistocene.

Faults along the Beaverhead-Jefferson basin.—Evidences of relative downfaulting appear in places along the sides of the large intermontane basin formed by Beaverhead and Jefferson valleys (Pl. 1, No. 36) and their arms or embayments extending up Blacktail Deer Creek at the southeast, Ruby River at the east, and Little Whitetail Creek at the north (Pl. 1, No. 35).

The basin is about 1000 square miles in area; its main part, 5 to 20 miles wide, is 70 miles long.

The drainage outlet, Jefferson Canyon, is a rugged gorge 1000 feet deep cut through the eastern rim from a point opposite Cardwell to the Three Forks basin. The Beaverhead River, Big Hole River, and Boulder River enter through smaller gorges from neighboring basins on the south, west, and north, respectively. A short distance south of Jefferson Canyon the rim is lowered considerably by a wide pass or wind gap (Pl. 5, G) which opens eastward to Three Forks basin.

The writer (1918, p. 141) presented evidence of a fault along the east side of Jefferson valley south of Renova. Tansley, Schafer, and Hart (1933, p. 4–6, Pl. 1) describe comprehensively the Tobacco Root (Jefferson) Mountains, which, for 20 miles south of Renova, form the east wall of Jefferson Valley. This section of the mountains has the general form of a fault block elevated along the west and slightly tilted eastward. Features of the west front characteristic of fault scarps include a regular base line, a steep and abruptly rising slope, and faceted spurs; the bases of the facets are aligned. From a point at the south opposite Twin Bridges, the fault line trends about N. 30° E. for 10 miles; beyond, its course averages about N. and includes offsets of a mile or more to the west at Spring Creek and half a mile to the east at Perry Creek. In places the fault line parallels the strike of the rocks, and in places it lies across it at varying angles.

Information available affords no close estimate of the amount of displacement. If the gradually descending east slopes of Jefferson Range and of the mountains on the opposite (west) side of Jefferson valley are dislocated parts of the Late Tertiary peneplain, the total displacement may be 5000 or 6000 feet (Pl. 5, K). The faulting may be chiefly Tertiary, but the preservation of the spur-end facets suggests that a considerable part of the displacement is not older than Pleistocene.

For several miles north and south of Jefferson Canyon the eastern rim of the Beaverhead-Jefferson basin presents a steep and regular front 1000 to 2000 feet high. South of the canyon the slope is particularly abrupt, and, as shown by the Three Forks geologic map (Peale, 1896), it cuts directly across several rock structures. The fault thus indicated strikes about north and separates the Tertiary from the older rocks. North of the canyon its projected course extends along the small rock gorge of the Boulder River and into the widened valley above. There the dip of the Tertiary beds and their relations to the older rocks indicate that the fault passes into a downfold along the east side of the valley which has depressed the Tertiary beds 1000 feet or more.

As it crosses the fault and enters the canyon, Jefferson River passes from alluvium to bedrock, and its current becomes accelerated. Upstream for several miles the river meanders sluggishly over the surface of alluvial "fill".

Physiographic evidence indicates a fault along the south side of the Blacktail Deer Creek arm of the Beaverhead-Jefferson basin that has relatively elevated the adjoining Blacktail Range.

The Blacktail Range is formed of tilted Cretaceous and older sedimentary rocks which, at the west near the entrance gorge of Beaverhead River, give place to Tertiary volcanics. The range presents a steep and regular north front that is parallel to the general strike of the rocks but crosses local structures. It rises abruptly from an alluvial plain and is drained by perpendicular streams of steep gradient flowing on bedrock in V-shaped valleys that are narrow at their mouths. Intervening spurs are faceted, and the bases of the facets are aligned on a regular course interpreted as the trace of the fault. From a height of about 3000 feet along the eastern part of the arm the range crest descends gradually westward to 1000 feet near the Beaverhead River. The back (south) slope of the range is a moderately uneven surface descending gradually toward Red Rock valley. North of the Blacktail Deer Creek valley is a slope developed on the older rocks and rising gradually from an irregular base line.

Assuming that this and the back slope of the range south of the arm are displaced parts of a former erosion surface, the relative downthrow of the arm was on the order of 3000 or 4000 feet. No evidence of recent movements was observed,

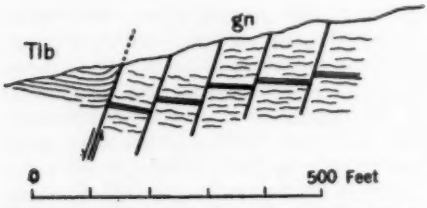

FIGURE 16.—FAULT AT WEST SIDE OF THE RUBY RANGE; CROSS SECTION

Tlb. Tertiary "lake beds"
gn. gneiss and schist

but the preservation of spur-end facets indicates that much of the faulting occurred within the Pleistocene.

Along the eastern side of Beaverhead valley the Tertiary beds are separated from the older rocks of the mountains along a line that trends about N. 30° E. Where Stone Creek crosses this line east of Dillon, it coincides with the exposure of a fault striking in the same direction and separating horizontal Tertiary (lake) beds from Precambrian gneiss, schist, and other metamorphic rocks (Fig. 16). The fault dips toward the basin, and a downward movement of the hanging wall is indicated by "drag" in the Tertiary beds. Within a few hundred feet the footwall block is cut by several slip planes parallel to the main fracture that record small downthrows in the same direction. The surface is a graveled terrace plain that is not dislocated by the fault. It is developed across the Tertiary deposits and continues for a mile or so upon the older rocks and ends at the mountain front, a gradually rising maturely worn slope without scarplike features. The fault is evidently older than the terrace plain, which is probably Pleistocene.

A road cut, excavated in 1939 on U. S. highway 10 along Little Pipestone Creek about 10 miles west of Whitehall, exposes a normal fault (Fig. 17) near the upper (west) edge of a gravel-capped terrace at 5300 feet altitude on the western side of the Jefferson valley. The fault trends northward, dips 70° E., and displaces Tertiary (?) stream-washed gravel that is locally gold bearing. Back of the fault line the surface rises steeply 500 feet or more to flats (5800-6000 feet altitude) preserved on spurs north and south of the creek. One flat occupies an area of

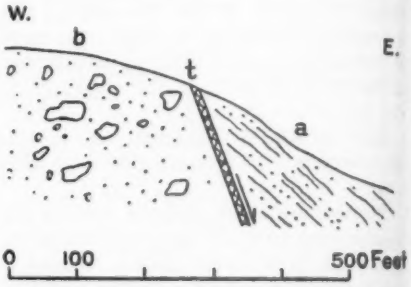

FIGURE 17.—FAULT AT LITTLE PIPESTONE CREEK; CROSS SECTION

a. alluvium—medium-textured
b. alluvium—with large boulders
t. fault gouge

2 or 3 square miles east of Grace Station on the Chicago, Milwaukee, St. Paul and Pacific Railroad. It cuts across granitic rocks and a small overlying patch of tilted Tertiary (Miocene ?) "lake beds" (Atwood, 1916, Pl. XXXVII A). The flats and the terrace plain east of the fault are interpreted as dislocated parts of the Old Valley or Bench No. 1 surface.

Continental and Elk Park faults.—South and east of Butte along the eastern edge of Upper Silver Bow Basin (Pl. 1, No. 38) or, as it is known locally, The Flat, is a fracture of post-Tertiary age called the Continental fault; its existence was first deduced by Weed (1912, p. 47–49) from physiographic evidence and afterward described by Sales (1914, p. 29–30) from exposed mine workings. More recently Corry (1931) has studied the fault.

Upper Silver Bow Basin is a small intermontane depression; its main features (Meinzer, 1914, p. 81–87) are typical of debris-filled valleys. Sloping surfaces extend with decreasing gradient from the edge of the mountains to the interior of the basin which is occupied by a broad flat. The sloping surfaces are trenched by shallow broad valleys whose floors merge with the central flat which has a gentle gradient toward the outlet gorge. Both the slopes and the flat are adjusted to the same base level but with

different gradients. Downcutting has ceased, and the streams are building up the valleys and the flat. The unconsolidated fill is generally several hundred feet thick and in places may be more than 1000 feet thick. Beneath the fill is granite similar to that of the surrounding mountains. Shafts and borings indicate an uneven bedrock surface that in places is lower even than the bedrock in the outlet gorge. In general it is lowest near the eastern edge of the basin.

Surrounding the basin is a generally massive rock wall broken only at the west where Silver Bow Creek discharges through a gorge obviously produced by stream erosion. The mountains on the north, south, and west vary greatly in height, slope, and outline. At the east, however, East Ridge (Pl. 4, fig. 2) presents a strikingly bold, abrupt, steep, and straight front 2000–3000 feet high. Details of this slope include short spurs showing transverse notches and some low foothills at the base that form a rock shelf which is out of adjustment both with the exposed mountain wall and with the buried rock floor beneath the flat.

At Woodville east of Butte a gap in East Ridge, reached by a steep ascent of about 900 feet from "The Flat," is the entrance to Elk Park (Pl. 1, No. 37) a flat-bottomed valley 1–3 miles wide that descends very gently in the opposite direction. At a distance of 10 or 11 miles the mountains close around the farther end of this valley except for a gorgelike drainage narrows.

From its profile and drainage pattern Weed (1912, p. 47) concluded that Elk Park, which now drains eastward to the Boulder River, formerly drained westward to Silver Bow Creek through the gap at Woodville. The reversal of drainage and the development of upper Silver Bow Basin and the bold front of East Ridge are explained by faulting, along a line parallel to the base of East Ridge, which uplifted and tilted the mountain block on the east and depressed the basin block on the west. The fault, as evidenced by the spacing of notches and other significant features, is composed of a number of more or less parallel planes one of which extends from the base of the foothills toward Meaderville. As exposed in the mine workings described by Sales (1914, p. 29), the faulting is distributed through a fissure zone 200–1000 feet wide having a general dip of 75° W. The western or hanging wall has moved south several hundred feet and downward probably 1500 feet.

The surface trace of the fault (Corry, 1931) is marked by lines of springs and zones of altered limonite-stained rock. One such zone exposed in the Bullwhacker pit is 50 feet wide. At the bend of the Great Northern Railway north of Meaderville a strand or slice of the fault is indicated by an exposure of 4 feet of breccia, clay, and gouge. The main fracture, however, is thought to reach the surface farther east along the foot of Rampart Mountain (Pl. 4, fig. 2). In the Birtha mine underground exposures of the fault include three fractures which at a depth of 100 feet strike north to east of north. Grooves on the walls indicate that the block on the west has moved relatively downward and northward. Maps of the Main Range mine (Corry, 1931, p. 24) show a fault zone about 200 feet wide at the 2000- and 2200-foot levels. The main fracture dips 70°–72° W. and carries 22 feet of gouge and clay with included masses of crushed granite. The pattern of the fractures is a network distorted by twisting so as to elongate the net horizontally in the plane of the vein (*i.e.*, north and south).

A vertical displacement of 1330 feet on the Continental fault is indicated by the difference in altitude between Elk Park gap and the bedrock under The Flat at the East Butte mine. The unconsolidated sediments that have accumulated in upper Silver Bow Basin since that area was depressed along the Continental fault are regarded as much younger than the Miocene beds to the west. Obviously, part of the fill is of Recent age, and part, as indicated by the observations of Meinzer (1914, p. 86), is probably Pleistocene. The fault cut and displaced the Butte veins after the oxidized and sooty chalcocite zones had developed (Sales, 1914, p. 12, 30; Pl. II). Meinzer (1914, p. 88) points out a difference in depth between two neighboring valleys near the south end of the flat that suggests recent deformation, and Weed (1912, p. 51) notes a possible slight movement on the fault plane between the years 1896 and 1906 as indicated by precise leveling. Presumably therefore the downfaulting of the basin has continued into Recent time.

Corry (1931) interpreted the east side of Rampart Mountain as the scarp of an east-

dipping fault that is cut off by the Continental fault. He estimates for the Elk Park fault a vertical displacement of several hundred feet with a horizontal component of 2400 feet as indicated by the displaced parts of a dike; the block represented by Rampart Mountain moved southward.

Fault east of Divide Trench.—Physiographic evidence indicates a fault along the east side of a trenchlike depression (Pl. 1, No. 39) formed by Deer Lodge Pass south of Silver Bow and the lower valley of Brown's Gulch to the north. As thus defined, the depression is 1–4 miles wide and about 25 miles long in a direction somewhat east of north. It is drained by streams flowing in opposite directions and at the south end is crossed from west to east by the Big Hole River and in the northern part from east to west by Silver Bow Creek, the headwater of the Clark Fork. Both streams enter and escape through gorges. Between them a flat watershed at about 5900 feet altitude forms the Continental Divide.

Along the east side of Deer Lodge Pass is an unnamed ridge; its crest, beginning with a height of 200–300 feet at Silver Bow Creek, ascends gradually to 2000 feet opposite the southern part of the Pass. The ridge presents a regular front (Pl. 5, L) slightly dissected by narrow downslope valleys. Spurs are somewhat oversteepened below, and their bases are aligned in a regular course interpreted as the trace of the fault. The back slope of the ridge is a plateau-like surface descending gradually eastward to Silver Bow Basin.

Escarpments in the floor of the Pass expose Tertiary "lake beds" dipping eastward toward the fault, and their relation to the underlying granite indicates displacements on two or more fractures parallel to the fault.

Along the valley of Brown's Gulch north of Silver Bow Creek the east mountain front is neither very prominent nor regular, but continuation of the fault in that direction is indicated by the reported rock relations at the Buzzard mine. A hole drilled from the bottom of a shaft on this property is said to have penetrated 1200 feet of the lake beds without reaching bedrock. The shaft is about a mile north of Silver Bow Creek and 1500 feet west of the projected fault line at which the granite rises above the surface.

The western side of the Trench is an uneven concave slope rising from an irregular base line to a maximum height of 3500 feet on Fleecer Mountain (altitude 9400 feet).

Faults along the Willow Creek-Rock Creek trench.—In a general view the valley of upper Willow Creek, the basin of Spring gulch, and a valley along Rock Creek, named in order from north to south, form a trenchlike depression (Pl. 1, No. 26) about 18 miles long, 1–2 miles wide, and 5000–6000 feet in altitude. It is drained by streams flowing in opposite directions and enclosed by mountains formed chiefly of broadly folded rocks of the Belt series with a general northward structural trend. Physiographic and other evidences of faulting, which has caused a relative downthrow of the trench, appear at its eastern side. The fault is broken into segments offset en echelon.

The mountains east of upper Willow Creek valley have the general form of an elevated and slightly tilted fault block. They present an abrupt and regular front rising steeply nearly 2000 feet from alluvial terrace plains to an even crest at 7700–7900 feet altitude. The slope, normal to east-dipping beds, is slightly dissected by streams perpendicular to the range front. Back of the crest is a wide somewhat undulating upland; its general surface, represented by flat or rounded spur backs and other divides, descends gently eastward (Pl. 5, E). The fault, as traced by aligned spur bases, trends nearly due north becoming somewhat concave toward that end of the depression. The west side of the trench rises more gradually from a rather irregular base line.

South of upper Willow Creek valley the fault turns eastward and dies out in Sheep gulch. It is succeeded by a segment offset a mile to the west which continues along the eastern side of Spring gulch basin. The fault, as exposed in a notch on the spur north of Spring gulch, is a west-dipping zone of breccia separating Tertiary "lake beds" (volcanic ash) from shale of the Belt series. Another segment, also offset to the west, begins at a notch in the spur south of Spring gulch and continues along the east side of Rock Creek valley 6 or 7 miles to Antelope Creek where it branches and dies out. As exposed back of Red Cliff, a landmark on the Rock Creek side of the spur, the fault dips 50° W and brings Tertiary conglomerate and vol-

canic ash beds in contact with argillite (Wallace formation) of the Belt series; the downthrow is at least 400 feet (Fig. 18). Continuing south along Rock Creek valley, the fault is marked by an escarpment rising back of slumped Tertiary beds.

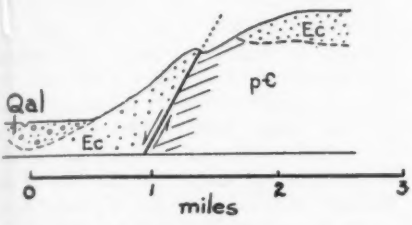

FIGURE 18.—FAULT BACK OF RED BLUFF, WILLOW CREEK-ROCK CREEK TRENCH

Qal. Quaternary alluvium
Ec. Eocene conglomerate
pC. Precambrian rocks

On the interpretation of general upland slopes east and west of the Trench as dislocated parts of the same surface, a relative downthrow is indicated along the upper Willow Creek valley of about 2000 feet (Pl. 5, E).

Bitterroot fault.—From physiographic and structural evidence Lindgren (1904, p. 38–58, 86, 87) concluded that a fault along the east front of the Bitterroot Range had caused a displacement of several thousand feet divided between an uplift of the range and a downthrow along the adjoining Bitterroot valley. Lindgren also believed the gneissoid structure of the granite along the mountain front was produced by the faulting. C. P. Ross[1] gives a more likely interpretation, however; he believes the gneissoid zone of the mountain front originated as did similar zones around the granitic batholith—namely, as an effect of compressive stresses during the intrusion of the igneous mass. Therefore the gneissoid structure is probably of late Cretaceous or early Tertiary age and hence much older than the movements which separated the range and the valley. The faulting, however, found the gneissoid zone an easy path to follow.

Bitterroot valley, one of the larger intermontane basins, lies between the bold and rugged Bitterroot Range on the west and the less steep and imposing Sapphire Mountains on the east. At the south the mountains close around the basin and at the north, a few miles beyond Lolo, draw near but leave a gap through which the drainage escapes.

The floor of the basin is 3200–4200 feet in altitude, about 50 miles long, and 10 to 12 miles wide near the middle. It is largely alluvial lowlands and low to moderately high gravel-veneered terraces or benchlands.

In the eastern side of the valley bedded tuffs and gravels, in which Douglass found Miocene vertebrate remains (Pardee, 1913, p. 234), are exposed in places along the terrace escarpments. Except for an area of Tertiary volcanic rocks south of Hamilton, the west side of the valley appears to be underlain by later (Quaternary) alluvium including glacial moraines and outwash from the Bitterroot Range. The presence of Tertiary beds in depth, however, is indicated by the occurrence of fossil wood in the Curlew mine. The Tertiary tuffs and gravel and the later alluvium together compose a valley "fill" of considerable depth in the central part of the basin. A well drilled for oil near Corvallis is reported to have ended in "soft beds" at a depth of 840 feet. In the outlet gap near Lolo the bedrock is apparently not far below the river channel. In the northern part of the valley along the base of the Bitterroot Range opposite Carlton and south of Big Creek low foothills of silicified gneiss, quartzite, and other pre-Tertiary rocks are detached from the mountain front by notches or trenches. On the east side the valley floor includes, near Corvallis, an area of moderately rough topography dominated by Chaffin Butte, a conical hill 500 feet high composed of the older rocks.

Glacial scouring has enlarged the canyons. At the north this effect is confined chiefly to the upper parts, but southward, near Hamilton and beyond, glacial scouring has widened the canyons to their mouths. Still farther south prominent morainal hills and ridges appear at the mouths of several canyons.

The Sapphire Mountains along the eastside of the valley present an irregular slope that rises more gradually than the front of the Bitterroot Range, and their general summit is a gently undulating, rather maturely dissected upland at 6500–8500 feet altitude, or 3000–5000

[1] Talk at meeting of the Geological Society of Washington, November 13, 1946.

feet higher than the valley (Pl. 5, A, E; Pl. 2, fig. 1).

Features significant of an uplift of the Bitterroot Range pointed out by Lindgren (1904, p. 38–41) include its imposing east front which rises with a uniform slope of 18°–26° to a crest

FIGURE 19.—FRONT OF BITTERROOT RANGE

Looking westward. Bitterroot Valley at Hamilton in foreground. Even sky line of Clearwater Plateau in background. Range front dissected by rocky narrow downslope canyons hung above large alluvial fans. Intervening spurs faceted. (Drawn from aerial photograph by the U. S. Forest Service.)

line marked by peaks 5000 to 6000 feet high (8500 to 9500 feet altitude). The slope is drained by perpendicular streams intrenched in deep canyons separated by narrow jagged ridges. Their streams flow on bedrock, are marked by rapids along their lower courses, and enter the valley above alluvial fans and cones that coalesce in a wide apron along the base of the range (Fig. 19). Back of the crest line the general summit descends 2000 feet or more to the surface of the dissected Clearwater plateau at an altitude of 7000–7500 feet (Pl. 5, A). The drainage divide, originally at the crest line, has migrated 2 or 3 miles to the west. Foothills at the base of the range just south of Big Creek (Lindgren, 1904, p. 49, 86, 87) are composed of crushed quartzite and limestone of uncertain age. At the Curlew mine a similar breccia forms an outcrop half a mile wide separated from the alluvial valley fill on the east by a normal fault dipping 45° E. A reported occurrence of fossil wood in the Curlew mine mentioned by Lindgren (1904, p. 87) was confirmed by Henry Buker, whom the writer interviewed in October 1936. Buker, who worked in the mine at about the time of Lindgren's visit, described the wood as a "petrified log" found on the 500-foot level of the old workings in cemented gravel forming the hanging wall of the fault.

The trace of the fault, as marked by the regular base of the range, is in line with trenches back of several foothills and with notches in the spurs south of Roaring Lion Creek and Blodgett Creek. The fault movements were distributed through a zone half a mile or more wide as indicated by the outcrop of breccia at the Curlew mine.

Lindgren (1904, p. 48) concluded that the Bitterroot fault both lowered the valley and elevated the range. He estimated the vertical displacement to be at least the difference between the height attained by the gneissoid zone and the valley—4000 to 6000 feet. On the theory that the generalized slopes on the back of the Bitterroot Range and the front of the Sapphire Mountains are the dislocated parts of the late Tertiary peneplain, a maximum downthrow of about 5000 feet is indicated (Pl. 5, A). The cross profile suggests a gentle westward tilting of the valley and of the mountain blocks.

In 1898 (Lindgren, 1904, p. 87), a downthrow of 1 or 2 feet toward the valley occurred on the Bitterroot fault opposite the Curlew mine; in 1899 the scarp was still visible for 1500 feet. This is the only direct evidence of any Recent displacement. Because the canyons of the Bitterroot Range had been excavated to nearly their present depth before the Wisconsin stage of glaciation, most of the faulting occurred before late Pleistocene time.

Fault at the northeast of the Missoula basin.—A fault that has relatively elevated the Squaw Peak Range along the northeast side of the Missoula basin is definitely indicated by spur-end facets strikingly aligned at the foot of the mountain slope. The relation of the slope to the structure of Tertiary "lake beds" within the basin is further evidence of faulting.

The Missoula basin (Pl. 1, No. 14) is an intermontane depression about 45 miles long and 7 to 8 or 9 miles wide, formed by the Missoula and Ninemile valleys. Its axis trends about N. 45° W.; it is widest at the southeast and narrows rather uniformly. Surrounding mountains form a rim 2000–4000 feet high broken by a gap at the south that admits the Bitterroot River, and penetrated by two rocky gorges, Hell Gate Canyon at the southeast and Alberton Narrows, about midway of the western side, through which, respectively, the Clark Fork River enters and leaves the basin. Squaw Peak Range and the northern end of the Jocko Range form the

northeast rim of the basin. At the southeast the rim is formed by Mount Jumbo, and University Mountain, respectively north and south of Hell Gate Canyon, and Mitten Mountain north of the gap which admits the Bitterroot River. A broad undulating maturely dissected plateau southwest of the basin includes a part of the Bitterroot Mountains (not the Bitterroot Range) and two ridges—the Petty Creek Divide and the Ninemile Divide. From its entrance at the northeast corner, the Clark Fork River crosses to the western side, is joined by the Bitterroot River, turns northwest along the base of the plateau to the outlet gorge where it receives Ninemile Creek coming from the opposite direction.

The basin floor 3000 to nearly 4000 feet in altitude is formed of alluvial plains along the streams, a low terrace of glacial lake silt in the central part, and belts of higher terraces and hills rising along the northeast side and in front of Mitten Mountain at the southeast. The city of Missoula is built on a wide-spreading alluvial fan extending along the Clark Fork from Hell Gate Canyon to the western side of the basin where it merges with lowlands along the rivers.

The belt of terraces and hills along the northeast rises 400 to 600 feet above the valleys of cross-cutting streams or to a general altitude of 3900–4000 feet. It is rather deeply covered with gravel mostly of local origin but containing extraneous boulders dropped from icebergs floating in a glacial lake. In places the surface has been deformed by slumping.

Beneath the gravel cover the terrace belt is composed of Tertiary "lake beds," chiefly fine-textured stream-washed gravel, sand, sandstone, shale, clay, and volcanic ash. Locally the beds include coal (Pardee, 1913, p. 240, 243) and contain an Oligocene or Miocene fossil flora (Jennings, 1920, p. 385–427). The gravel beds are composed of waste from the Precambrian Belt series and other rocks of the near-by mountains and include much arkosic material for which the only available source is the granitic rocks of the Bitterroot Range along Bitterroot valley 20 miles and more to the south.

Exposures of the Tertiary not disturbed by slumping indicate deformation and faulting. The most definite structure is an open syncline trending from Grant Creek northwestward 8 or 10 miles toward O'Keefe Creek. Its northeastern flank is sharply upturned next to the mountain front where dips of 44°–70° appear in the workings of the Thibodeau mine on Ravalli Creek (Sec. 26, T. 14 N., R. 20 W.). Dips on the southwestern flank as exposed in the Hell Gate mine, a short distance north of Missoula, and in the Glasscock mine on Butler Creek, range from 20° to 45°. Only superficial exposures of the Tertiary "lake beds" were observed northwest of O'Keefe Creek except at the open cut of a placer mine on Kennedy Creek where alternating beds of coal and shale, apparently undisturbed by slumping, dip 45° NW. Poorly exposed south of Pattee Creek, the Tertiary "lake beds" are upturned 20°–30° along the foot of Mitten Mountain. Quartzite and other pre-Tertiary rocks form hills in front of the outlet gorge and near the southeastern corner of the basin and are exposed in the terrace east of Stark Creek.

The mountains that surround the Missoula basin are composed of deformed quartzite, sandstone, argillite, and similar rocks of the Belt series with a relatively small amount of later intrusives, chiefly diorite sills and dikes. In general the bedded rocks strike northwestward parallel to the axis of the valley, but there are local variations. At O'Keefe Creek sandstone and argillite at the base of the mountain slope dip steeply northward, and the bedding is largely obscured by a cleavage or schistosity inclined 45° S. or in the same direction as the slope. Farther northwest at Kennedy Creek and Stark Creek beds that strike NW. range in dip from 45° N. to vertical.

Along the northeastern side of Missoula basin from Six Mile Creek northwestward, a succession of triangular spur-end facets at the base of the Squaw Peak Range represent the scarp of the fault. The facets are aligned along their bases in a regular course slightly concave to the basin. They rise steeply and abruptly several hundred feet from shallow notches or trenches back of the belt of hills and terraces. The spurs, narrow-crested above the facets, ascend more gradually to the summit of the range. Backsets in the profiles of the facets (Fig. 21) indicate that faulting was distributed among parallel planes in a zone several hundred feet wide. The fault planes parallel the general strike of the

older rocks but cut them on the dip, and at Six Mile Creek cross a local fold. Thence eastward the spur-end facets are rather deeply worn and

Creek, a stream descending the opposite side of the range, but has not yet moved the drainage divide back to a position of equilibrium.

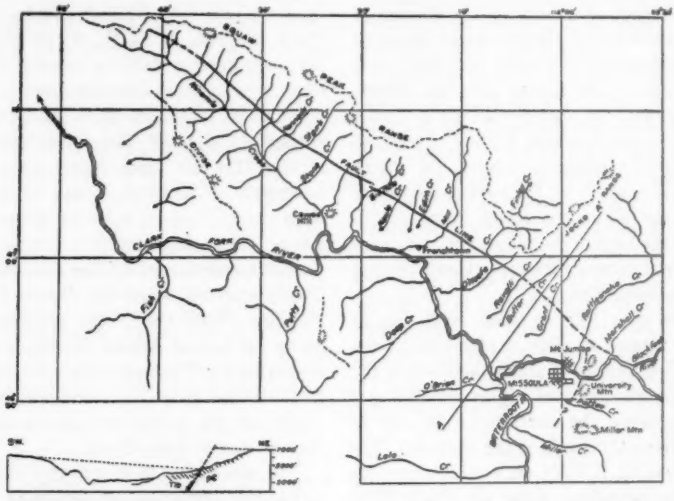

FIGURE 20.—FAULT AT THE NORTHEAST OF THE MISSOULA BASIN; PLAN AND SECTION
Tlb. Tertiary "lake beds" pC. Precambrian rocks

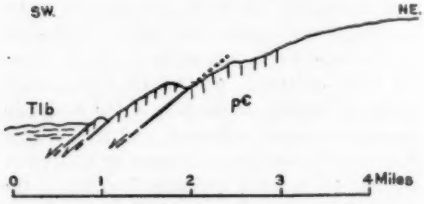

FIGURE 21.—FAULT SCARP AT SOUTHWEST BASE OF SQUAW PEAK RANGE; BACKSETS IN SPUR PROFILE
Tlb. Tertiary "lake beds"
pC. Precambrian rocks

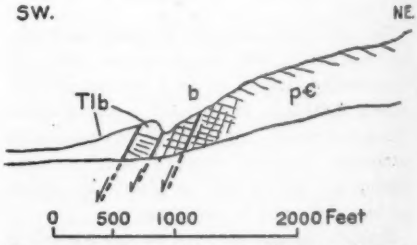

FIGURE 22.—FAULT ZONE AT O'KEEFE CANYON; CROSS SECTION
Tlb. Tertiary "lake beds"
pC. Precambrian rocks
b. schistose zone

rise from a trench excavated by opposite-flowing streams along the trace of the fault. At Edith Creek the fault crosses another fold and at O'Keefe Creek coincides with a schistose zone (Fig. 22). Beyond O'Keefe Creek the projected trace of the fault is in line with small notches on terraced spurs at the base of the mountain front and passes through the saddle north of Mount Jumbo and, at Marshall Creek, coincides with a zone of breccia with southwestward-dipping slip planes.

Because of the relative uplift of the range, O'Keefe Creek is invading the basin of Finley

The peneplain, represented by the undulating plateau southwest of the basin and by flat or gently sloping uplands on the southern end of the Jocko Range at the northeast, has been relatively downthrown 2000 feet or more toward the southwest (Fig. 20, AA'). Most of this displacement probably occurred in Pliocene or early Pleistocene time.

Jocko fault.—Spur-end facets and other features of the bold and regular western front of the Jocko Range give evidence of a fault that

has relatively elevated the range and lowered the adjoining Jocko Valley (Pl. 1, No. 15).

Jocko Valley including Evaro Pass, its southern arm, is an irregular intermontane basin 2–8 miles wide and about 12 miles long in a northwest direction. In the main part its floor, 2800–3600 feet in altitude, is chiefly an alluvial plain that descends gradually from 3600 feet altitude near the foot of the Jocko Range to 2850 feet at the northwest corner. Several glacial moraines from canyons in the Jocko Range extend short distances over the plain, and toward the northwest there are low terraces of glacial-lake silt along the northern side of the valley. Insofar as observed, the valley contains no sediments similar in composition to the Tertiary "lake beds" that occur extensively in the Missoula basin not far to the south.

Evaro Pass, an elevated arm of the Jocko Valley, extends 5 or 6 miles southward along the Jocko Range and ends at a comparatively low ridge that forms part of the northeastern and relatively upthrown rim of the Missoula basin. O'Keefe Creek working headward from that basin has broken through the ridge at a point southwest of Evaro capturing drainage from Finley Creek. The floor of Evaro Pass includes a nearly level flat that gives place on the east and west to terrace-plain escarpments 50–100 feet high ascending gradually back to the mountains. At the south the flat gives place to the canyon of O'Keefe Creek. At the north a surface descends rather steeply to the plain in Jocko Valley.

The mountains surrounding Jocko basin are formed of folded shales and sandstones of the Belt series; the structures trend north to northwest. From the rather steeply rising Squaw Peak Range at the southwest several large uneven spurs project. One of these extends to the Bison Range opposite and encloses the basin on the north. Both ranges are overshadowed by the Jocko Range which rises steeply and abruptly along the east to a height of 4000 feet or more. The Jocko River enters from a narrows at the northeast and leaves through a gorge at the northwest.

For 10 miles or more along Evaro Pass and Jocko Valley and the gorge of the Jocko River, the Jocko Range presents a bold and regular front dissected by steep narrow perpendicular valleys. The intervening spurs end in facets aligned about N. 30° E. slightly concave toward the basin and developed across the rock structures. A lateral moraine at the faceted end of the spur north of Big Knife Creek appears to have been downthrown (Fig. 23), leaving a

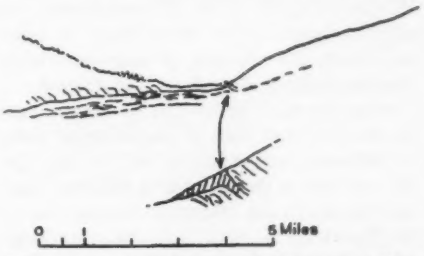

FIGURE 23.—JOCKO FAULT; SCARP NOTCH IN SPUR

small patch of glacial debris on the rock surface above the facet.

As measured by the height of the larger facets, the displacement at the axis of the valley is at least 2000 feet. The rather steep descent from Evaro Pass to Jocko Valley is partly due to embankments of shore drift in the ancient glacial lake, but, as exposed by the trench of Finley Creek, the bedrock surface also bends downward toward Jocko Valley, suggesting downwarping toward the axis of the basin.

A small movement in late Pleistocene time is indicated by the displaced moraine at Big Knife Creek, but, because of the deep trenching of the mountain front, most of the uplift must have occurred much earlier.

Faults along the Rocky Mountain Trench.—Daly (1912, pt. I, p. 26 *et. seq.*) gave the name Rocky Mountain Trench to a chain of valleys that form a "narrow, wonderfully straight depression" in the western side of the Rocky Mountains extending from Flathead Lake northward into British Columbia.

The part of the Trench within western Montana is about 75 miles long, trends about S. 30° E., and is formed (from north to south) by the Tobacco Plains (Pl. 1, No. 3), Stillwater Valley, and Kalispell Valley (Pl. 1, No. 4). At the south end of Kalispell Valley the wedgelike Mission Range, rising gradually from a plain, splits the Trench into eastern and western arms. The eastern arm continues the southeastward course of the main Trench and possesses the

trench characteristic required by Daly's definition—drainage of segments by opposite-flowing streams. It is about 125 miles long and is formed in order by the Swan, Clearwater, Blackfoot, and Avon valleys. The western arm formed by the basin of Flathead Lake and the Mission Valley (Pl. 1, No. 8) extends about 50 miles due south to the Bison Range. It lacks the trench characteristic of opposite-flowing streams; drainage throughout is southward.

Along the main trench and its western arm are the Whitefish fault at the northeast sides of Stillwater and Kalispell valleys and the Mission fault at the east side of Mission Valley and Flathead Lake. Along the eastern arm of the Trench are the Swan fault at the northeast sides of Kalispell, Swan, and Clearwater valleys (Pl. 1, Nos. 7, 16), a fault at the northeast side of Blackfoot Valley (Pl. 1, No. 18), and a fault at the northeast side of Avon Valley (Pl. 1, No. 23).

Along both sides of the Trench and its arms most of the mountains are sandstones and argillites of the Belt series with a few sills or dikes of diorite. Along Avon Valley, however, at the end of the eastern arm, these rocks give place largely to formations ranging from Cambrian to Cretaceous. These and the Belt rocks are strongly deformed by structures of late Cretaceous or early Tertiary age having a general north-northwest trend. Throughout the trench and its arms, their eroded surface forms an unconformable "bedrock" floor beneath Tertiary sediments and Quaternary deposits, the latter chiefly of glacial origin. In places on the slopes west of Avon and Blackfoot valleys Tertiary lavas overlie the older rocks.

A Quaternary ice stream that originated in British Columbia moved south along the Rocky Mountain Trench and down its western arm into Mission Valley. At the Canadian border it was 5000 feet deep (Daly, 1912, pt. II, p. 585), and its abrasive effects, particularly severe along Tobacco Plains and Stillwater valleys, are noticeable as far south as the shores of Flathead Lake. The glacier left extensive sheets of drift which, as exposed in Mission Valley, indicate two advances of the ice. Another ice sheet, formed by confluent glaciers of local origin, occupied all the eastern arm except Avon Valley. It left the floor of the arm generally covered with moraines, outwash, and related deposits.

The mountains along the east or northeast sides of the Trench and its arms as a rule present bold, steep, and regular fronts that rise either directly from a lowland plain or from notches or trenches back of foothills. Perpendicular streams dissected the slope. Spurs are faceted, and the bases of the facets are aligned. The front slopes rise to crests 2000–4000 feet or more high that are surmounted here and there by a 500- or 1000-foot peak or ridge. From the crest broad general upland surfaces descend gradually in the opposite direction.

The western sides of the Trench and its arms rise gradually from outlines winding in and out around foothills and projecting spurs. The slopes are maturely dissected by streams that have become adjusted to the rock structures. Along the main Trench and its south arm the comparatively low Selish Mountains occupy a wide area and present an old-looking topography with rounded knobs and smoothed ridges reflecting details in the structures resulting from the Laramide revolution.

Northeast of the main Trench the Whitefish, McDonald, and Galton ranges present a strikingly bold steep front rising abruptly 3500 or 4000 feet to an even crest with few peaks several hundred feet higher. Back of the crest is a broad upland rather maturely dissected by glaciated valleys; its general surface descends gradually eastward toward the valley of the North Fork of the Flathead River. Whitefish Creek, Grave Creek, and some smaller streams have worked back through the crest for different distances capturing parts of the east-flowing drainage but the divide has not yet migrated to a position of equilibrium.

Whitefish Creek and Grave Creek separate the mountain front into three segments of about equal length; the middle segment is advanced about 2 miles beyond the others. The mountain front, in particular the advanced segment, was severely worn by the great glacier that moved from British Columbia southward (Davis, 1920, p. 90).

The slope described is interpreted as representing the worn scarp of a fault, and, therefore, the trace of the fault is somewhat out in the Trench floor. On the basis of interpreting the

upland at the northeast and the gradually rising slope of the Selish Range at the southwest as dislocated parts of the Late Tertiary peneplain, the displacement is on the order of 5000 feet (Pl. 1, Profile A-A). Both blocks were slightly tilted northeastward.

Mission Range (Pl. 4, fig. 3), a striking scenic feature of western Montana (Elrod, 1901, p. 621–623; 1903, p. 97–122; Pl. XVIII–XLVI), is described by Davis (1916, p. 267–268) as having the appearance, from the west, of a gently tilted and moderately dissected fault block. Its low northern end emerges from beneath the glacial deposits that floor the wide plain of Kalispell Valley northeast of Flathead Lake. Southward its moderately uneven crest rises gradually until, near an abrupt descent at the southern end, it gains an altitude of 9800 feet (Mt. McDonald) or nearly 7000 feet above the valley.

The mountain front is steep, regular, and rises abruptly, its north-south base line is approximately the trace of the fault. The front slope is drained by steep narrow perpendicular valleys not adjusted to the structure. In profile the intervening spurs are slightly convex down to a point, generally several hundred feet above the valley, where, as the slope passes onto lateral moraines, the profile becomes irregular or concave upward. On the spur north of Post Creek and near the lower end of McDonald Lake the fault and an eastern slice are marked by a double notch. There the main fracture is inclined about 45° W. and drops buff limey argillite (Wallace ? formation) against pink banded sandstone (Ravalii ? group). Below the notch the spur profile descends more gradually on the lateral moraine of a glacier from Post Creek. Elsewhere along the east side of Mission Valley, at the foot of the steeply rising slope, is a fringe of irregular, gently descending spurs and benches formed by alluvial cones and the moraines of local mountain glaciers. North of a branch of Mud Creek east of Polson the trace of the fault is marked by an oversteepened spur end. On a spur north of Mission Creek it passes through a notch which drops the spur profile about 100 feet. Farther south the trace follows a trench back of foothills at St. Mary's Lake (Fig. 24). There west-dipping purple shale (Spokane ? shale) is in fault contact with eastward-inclined argillite (Wallace ? formation). To the north along Flathead Lake, roughly faceted spur ends were interpreted by Davis (1920, p. 94) as probably formed by glacial scour. He concluded that the fault trace lies somewhat out from the base of the facets.

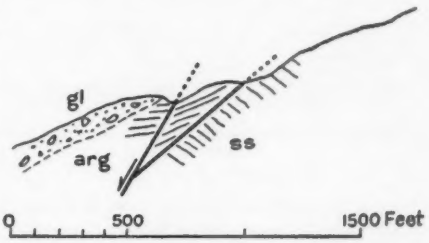

FIGURE 24.—MISSION FAULT; CROSS SECTION SOUTH OF ST. MARY'S LAKE
gl. glacial moraine
arg. argillite
ss. sandstone

In contrast to the relatively simple eastern edge of this arm of the Trench, its western outline, formed by the intersection of valley and lake surfaces with the projecting spurs of the less steeply ascending Selish Range, is exceedingly irregular.

Interpreting the generalized eastern slopes of the Selish and Mission ranges as displaced parts of the peneplain, the maximum throw of the Mission fault near the latitude of St. Ignatius is 8000 feet or more (Pl. 1, Profile B-B′). The movement probably took place during late Tertiary or early Quaternary time.

The Swan Range (Pl. 1) extending from the notch of the Flathead River at Columbia Falls southeastward for 80 miles has the general form of an elevated and tilted fault block. Toward Kalispell, Swan, and Clearwater valleys on the southwest it presents a bold and regular front 3000 to 4000 feet high. The slope rises steeply and abruptly and is moderately dissected by downslope streams not adjusted to the structure. It trends with the general strike of the rocks but intersects the dip. The back slope of the range descends more gradually toward the South Fork valley and is rather maturely dissected by streams in a pattern largely controlled by rock structures.

Spur-end facets of the mountain front along Kalispell valley were regarded by Davis (1920,

p. 87–89) as formed by the abrasion of the great glacier that descended the Main Trench. He stated that the facets decrease in height southward and cease near the entrance of Swan Valley where the spur profiles "descend gradually to the base line." However, this

FIGURE 25.—SOUTHWEST FRONT OF BLACKFOOT MOUNTAINS

condition, in Swan Valley at least, is due to the fact that the spur profiles below are carried on lateral moraines extending from the oversteepened or faceted spur ends. Toward the southern end of Swan Valley the spur-end facets rise above glacial deposits. In this valley, which apparently was not invaded very far by the Main Trench glacier, the trace of the fault coincides with the base line of the oversteepened spurs but in Kalispell Valley, as suggested by Davis, the trace is probaly somewhat out from the glacially eroded spur facets. To the southeast at the head of Swan Valley and along the Clearwater Valley beyond, the fault trace is marked by trenches back of an extensive group of foothills that separates the Clearwater and Blackfoot valleys (Pl. 1, Nos. 16, 18). As thus traced its course is about N. 35° W. at the south end turning slightly concave toward Clearwater Valley.

The opposite side of Swan Valley is a maturely dissected slope rising rather gradually to the crest of the Mission Range. This surface and the back slope of the Swan Range, interpreted as dislocated parts of the Late Tertiary peneplain, indicate (Pl. 1, Profile B-B′) a displacement on the order of 500 feet near the southern end of Swan Valley. The movement includes an uplift of the Swan Range, a downthrow along Swan and Clearwater valleys, and a gentle eastward tilting of both blocks.

Clapp (1932, p. 24–27, Pl. I) described a fault along the base of the Swan Range as one of a group of longitudinal east-dipping fractures of late Cretaceous or early Tertiary age on which the east (hanging) wall was thrust upward. He observed, however, that later normal faulting along the thrust faults is indicated by tilted erosion surfaces such as the eastern slopes of the Mission, Swan, and Flathead ranges and other physiographic features. Therefore the normal faults, although of the same strike, are later than the thrust planes.

In general the mountains northeast of Blackfoot Valley present the bold steep front (Fig. 25) and other features of a worn fault scarp. The trace of the fault, as marked by the base of the slope, is separated by offsets of 2 miles or less into segments of different lengths arranged en echelon (Fig. 26). Looking northwestward each segment is displaced to the left or southwest of the one preceding. The segments trend from N. 30° W. to about N. 70° W., their combined course being concave toward the valley. At the southeast the fault ends in a notch in the spur south of Arrastre Creek and at the northwest in a trench at Cottonwood Lake back of a foothill spur between the Blackfoot and Clearwater valleys.

The valleys of Monture Creek and the North Fork of the Blackfoot River extend well back into the mountains. Elsewhere the front slope is moderately dissected by short perpendicular streams. From its crest the general upland surface descends gently northeastward. The Garnet Range on the opposite (southwest) side of the valley rises more gradually from an irregular base line. These surfaces are interpreted as parts of the Late Tertiary peneplain. Their profiles projected to the fault plane indicate a downthrow on the order of 3000 feet at the southwest base of the Blackfoot Range.

Little Blackfoot River enters Avon Valley (Pl. 1, No. 23) from a narrows at Elliston in the southeast corner. Thence the stream crosses to the west side and escapes through a gorgelike narrows at the southeastern end of the Garnet Range. The northwestern part of the valley is drained by Nevada Creek, a tributary of the Blackfoot River. The basin thus possesses the trench characteristic of drainage by opposite-flowing streams.

The floor of Avon Valley is mostly gently sloping alluvial terraces developed across Tertiary volcanics and "lake beds." Moderately wide to narrow alluvial lowlands border the streams. A local glacier descending Three Mile Creek from the mountains at the northeast

deposited a moraine at the side of the valley. The Tertiary "lake beds" continue northwestward along Nevada Creek and disappear beneath the glacial deposits of Blackfoot valley.

Continential Divide and on the west by a broad upland formed by the Whitefish and Galton ranges. The Flathead River enters from the north, follows a course along the west side

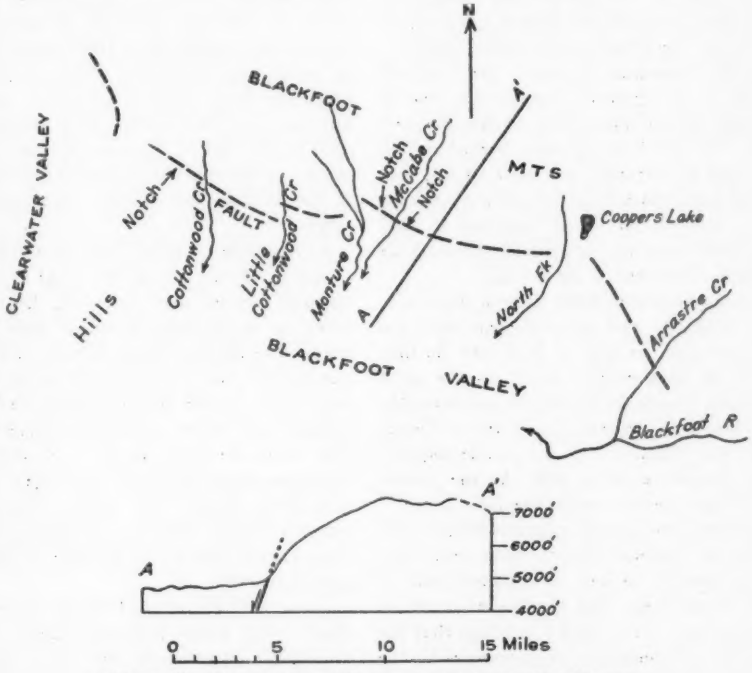

FIGURE 26.—FAULT AT THE NORTHEAST OF BLACKFOOT VALLEY

At the northeast the mountains present a steep and rather maturely dissected front. Along its base aligned, spur ends and spur notches trace a normal fault that is exposed at the Denver mine in Ophir Gulch (Pardee and Schrader, 1933, p. 34). The fault, as traced, is somewhat concave to the valley and is offset about 2 miles at Carpenter Gulch, the northwestern part being advanced.

The height of the blunt or faceted spur ends indicates a relative uplift of the mountain block of at least 1000 feet.

Faults along the Flathead Trough.—An intermontane basin (Pl. 1, No. 5)—Flathead Trough (Daly, 1912, pt. 1, p. 117)—extends for about 40 miles along the western side of the Glacier National Park and continues northward several miles farther into Canada. The basin is 6 to 10 miles wide and enclosed on the east by the Continental Divide and on the west by a broad upland formed by the Whitefish and Galton ranges. The Flathead River enters from the north, follows a course along the west side of the basin and leaves to Kalispell Valley through a winding gorge at the southwest.

The basin floor 3500 to 5000 feet in altitude is largely occupied by massive transverse ridges that rise 500 to 1000 feet above intervening streams and stand like buttresses against the lofty, precipitous spurs of the Continental Divide. The river is bordered with narrow alluvial lowlands that give place to low narrow terraces on the west. The high terraces are underlain by glacial drift which in turn overlies Tertiary "lake beds." The Tertiary beds, probably Miocene or Pliocene, contain lignitic coal in places and are deformed by faulting (Willis, 1902, p. 327; Daly 1912, pt. I, p. 86–88; pt. II, p. 571; Erdmann, 1947, p. 63).

The mountains along the eastern side of the Trough include many of the glacially sculptured ridges and peaks that characterize Glacier

National Park. From the general plain of the high terraces, they rise abruptly 3000 to 4000 feet forming the skeleton of what was once a wide upland of broadly folded Belt rocks. The western side of the Trough rises steeply for about 2000 feet and then ascends gradually to the crest of the Whitefish and Galton ranges.

At the Canadian boundary the Flathead Trough is a "graben" downthrown several thousand feet by faults along the east and west (Daly, 1912, pt. I, p. 117, map sheets 1 and 2). The fault on the east, as traced by blunt or faceted spur ends and notches back of foothills, trends about S. 40° E. It continues at least to a notch in the spur beyond McDonald Lake at the southern end of the Trough.

The oversteepened lower slope of the mountains along the west probably represents the worn scarp of the fault at that side. As thus traced the fault extends nearly to the south end of the Trough. In this stretch it is separated into three main segments by offsets at Camas Creek and Moose Creek, the middle segment being receded about a mile. At the Camas Creek offset the river enters the outlet gorge.

From the stratigraphic relations Willis (1902, p. 343, 344) concluded that the valley was downthrown toward the west by a normal fault of great displacement. The cross profile north of Logging Lake (Pl. 1, A-A′) indicates that the Late Tertiary peneplain, as represented by the general summits of the adjoining mountains, was displaced about 5000 feet by the fault on the east and about 3000 feet by the fault on the west.

Faults at the southwest of Flathead Range.—The northern part of the Flathead Range (Pl. 1) has the general form of a fault block elevated along the southwest and tilted gently backward. In the southern part, a fault along the same southwest side of the range is indicated in places by features of the mountain front.

The Flathead Range extends from West Glacier (Belton), the western entrance, to Glacier National Park, southeast about 75 miles to a junction with the Continental Divide at the head of the White River. It is formed chiefly of Precambrian sedimentary rocks of the Belt series with considerable areas of early Paleozoic beds in the southern half (Clapp, 1932, Pl. I). The rocks dip eastward.

The South Fork of the Flathead River flows northward along the western foot of the Flathead Range for 60 miles. In this course the river valley is made up of alternating narrows and wider basinlike sections. One widened section south of Riverside Creek is 25 miles long; another south of the Black Bear ranger station, including a flat called Big Prairie, is 14 miles long. The floors of these depressions range in altitude from 3500 to 3800 feet at the north to 4500 to 4800 feet at the south, and are formed of narrow alluvial flats, extensive uneven areas of glacial drift, and irregular rock knobs and ridges.

At Riverside Creek the river departs from its course along the foot of the range to enter a narrows farther west in which the stream continues to its mouth about 15 miles farther north. The Hungry Horse damsite is a gorge-like constriction of this narrows about 5 miles below the entrance. North of Riverside Creek a straight and rather narrow trenchlike depression takes the place of the river valley and continues along the foot of the range to its end near West Glacier. The trench is drained by opposite-flowing streams, and its floor, ranging from 3500 to 4500 feet in altitude, is formed of glacial deposits.

Along both the widened section of the South Fork valley above Riverside Creek and the trenchlike depression to the north, the Flathead Ranges rises steeply and abruptly about 3000 feet to a rather even general crest at about 7000 feet altitude. Here and there is a peak as much as 1000 feet higher. The front slope cuts across eastward-dipping rocks, is submaturely dissected and drained by perpendicular streams. It presents spur-end facets aligned along their bases in a northwest course that marks the trace of the fault. The longer and more maturely dissected back slope descends more gradually toward the valley of the Middle Fork.

To the Black Bear-Big Prairie section the maturely dissected mountain front, 3000 feet high, presents steep spur-end facets aligned along their bases in a northwest course that is interrupted at the White River about midway by an offset of a mile; the southern part is advanced.

To the southwest across the South Fork River the general surface of the maturely dissected back slope of the Swan Range rises

gradually. Assuming this slope and the back (east) slope of the Flathead Range to be the displaced parts of formerly continuous Late Tertiary peneplain, a relative uplift of the Flathead Range on the order of 3000 feet is indicated by a cross profile south of Riverside Creek (Pl. 1, B-B′).

Hope fault.—The Hope fault (Calkins, 1909, p. 55; Anderson, 1930, p. 44–47; Gibson, 1948; Jenks, 1932) extends from the vicinity of Hope, Idaho, southeastward as far at least as the Vermillion River, a distance of 50 miles. It cuts broadly folded rocks of the Belt series locally displacing them several thousand feet both horizontally and vertically; the downthrow is to the southwest. Topographic features beyond the Vermillion River indicate that the fault continues southeastward at least 20 miles farther. Apparently it dies out up Cherry Creek, a south tributary of the Clark Fork, opposite the Thompson River. The faulting was distributed among parallel fractures of a rather wide zone which controlled the location of the Clark Fork valley (Anderson, 1930, p. 8).

From Pend Oreille Lake to the Thompson River the Clark Fork valley (Pl. 1, No. 12) is a steep-sided depression 2 to 4 miles wide that forms the southeastern arm of the Purcell Trench. The enclosing mountains are broadly folded Belt rocks trending generally north-northwest. The valley floor is underlain chiefly by Pleistocene and Recent lake and stream deposits. Through these a few knobs and ridges of the older rocks project.

The southwest side of the trough rises steeply about 3000 feet to a general surface ascending gradually back to the summit of the Coeur d'Alene or Bitterroot Mountains. Along the northeast the Cabinet Mountains present a bold, fairly regular front rising steeply 4000 to 4500 feet to a rather maturely dissected upland with a somewhat undulating general surface descending gradually northeastward. Bull River, Vermillion River, Graves Creek, and Thompson River have cut deep valleys in the front slope and for several miles into the upland beyond where they have captured formerly eastward-flowing drainage. Intervening stretches of the mountain front are moderately dissected by comparatively short downslope valleys.

The uplands on opposite sides of the trough are interpreted as representing parts of a former surface—the Late Tertiary peneplain—dislocated by the Hope fault, the southwestern part being downthrown about 1000 feet. Subsequently the river excavated its troughlike valley along the fault zone to its present depth. Therefore the upper part of the northeast mountain front may be described as a fault scarp and the lower part as a fault-line scarp. To judge by the depth to which erosion deepened the valley the fault displacement occurred not later than early Pleistocene.

Fault north of the Savenac Trench.—The steep and regular mountain front north of the Savenac trench is interpreted as the scarp of a fault that relatively elevated the mountains and depressed the trench.

Going west-northwest from the Clark Fork River at St. Regis, the Savenac Trench (Pl. 1, No. 13) is formed in order by the valley of Mullan Creek, a gap across the divide known as the Camels Hump, and a stretch crossed by several streams flowing southward to the St. Regis River. The depression is about 25 miles long, mostly 1 to 2 miles across, and widened to 3 miles at the Savenac Tree Nursery of the U. S. Forest Service where, for a short distance, it is open on the south to the valley of St. Regis River. It extends to the west fork of Packer Creek near the Idaho-Montana divide.

The trench floor is occupied about equally by flood plains, alluvial terraces, and rock knobs and ridges. Its southern side is formed by a linear series of ridges and hills a few hundred to 1000 feet high separated by transverse stream valleys. The mountains along the north present a bold and abrupt scarplike front rising steeply 1500 to 2000 feet from a regular base line to an upland with an even or slightly undulating general surface with rather wide, flat or rounded ridge tops at 6000 to 6500 feet altitude. Both the front slope and the upland are rather maturely dissected, and spurs descending to the trench are blunt or truncated and aligned along their bases. The fault trace, as marked by the base line, is slightly concave toward the depression and is offset a mile or less at Twelve Mile Creek about a third of the way from east to west; the eastern part is advanced toward the south.

On the Camels Hump, highway excavations expose a breccia along the trace of the fault;

the rock structures on opposite sides are discordant. Along the valley of Mullan Creek to the east the fault passes through notches in projecting spurs.

To the south the Bitterroot Mountains form an undulating maturely dissected plateau thought to represent the Late Tertiary peneplain. From Savenac Ranger Station to St. Regis, where it enters the Clark Fork, the St. Regis River occupies a narrow gorgelike valley a little south of the trench. The stream is deeply intrenched in the Belt rocks, and its course evidently was established on the peneplain before that surface was displaced by the faulting.

The positions of the peneplain on the mountains north and south of the trench indicates a relative downthrow of 1000 feet or more along the north.

Fault along Bull Lake Trench.—Named from a water body near its south end, the Bull Lake Trench (Pl. 1, No. 1) is a north-south depression 1–4 miles wide and about 25 miles long. On the east it is enclosed by the lofty, rugged Cabinet Range (Gibson, 1948; Pl. 1; Pl. 9, Profile B B′) south of the river and the Purcell Mountains to the north. Along the west is a somewhat less elevated unnamed range, mapped as part of the group called the Cabinet Mountains. The Kootenai River crosses the northern part of the trench from east to west. It enters from a gorge between the Cabinet Range and the Purcell Mountains and leaves through a less deep and ruggeg narrows at the northern end of the Cabinet Mountains. The northern part of the trench drains southward to the river through O'Brien Creek. Bull Lake, at the western side and near the south end of the trench is drained by Lake Creek flowing north to the river. Beyond a low divide a short distance south of the lake, Bull River, which enters from a canyon at the east, turns south and continues through a winding gorgelike narrows to its junction with the Clark Fork River.

The trench floor, 1 to 4 miles wide and about 25 miles long, is formed mostly by plains at altitudes of 2000 to 2500 feet underlain by glacial lake silt. In places small rock knobs project through the silt, and beneath that deposit is a layer of glacial drift exposed along the wide 400-foot deep channel of the Kootenai River. The surrounding mountains and the bedrock beneath the silt and drift are formed chiefly of sedimentary rocks of the Precambrian Belt series locally intruded by granitic bodies and diorite sills.

The west side of the trench rises steeply 1000 to 2000 feet to a general upland surface that ascends gradually back for 8 or 10 miles. The basin occupied by Bull Lake, from which cliffy slopes rise along the west, was excavated by glacial erosion along the Lenia fault (Calkins, 1909, p. 52, 54, 68, 69), a Laramide structure with downthrow to the east.

Along the east side of the trench the mountains present a bold, steep and regular front, 4000 to 5000 feet high, submaturely dissected by perpendicular streams not adjusted to the structure, narrowed toward their mouths, and tending to hang above alluvial cones. The intervening spurs are oversteepened or faceted below, and the bases of the facets are aligned in a regular course that forms the trace of the fault (Gibson, 1948, p. 42–45, 63; Pls. 1, 6, 9). The fault fracture is exposed east of Bull Lake (Calkins, 1909, p. 67, 68, Pl. I). There it dips 45° W. and carries a schistose breccia. At Porcupine Creek a few miles to the north the fault trace is marked by a notch back of a small foothill, and at Savage Lake still farther north it passes into a wide shear zone. At the gorge of the Kootenai River the fault is offset about a mile to the west. Continuing northward a distance of 2 miles up the valley of O'Brien Creek it is again offset half a mile to the west and beyond that point apparently dies out within a few miles. To the south beyond Bull Lake the fault appears to die out up the South Fork of the Bull River.

Assuming the general upland areas on both sides of the trench to represent the Late Tertiary peneplain, their relative positions indicate a downthrow of as much as 5000 feet on the fault at the east. The displacement was accompanied by a slight eastward tilting of both the mountain block and the block beneath the trench.

Kootenai Falls (Gibson, 1948, Pl. 2) a cascade along the channel of the Kootenai River in the gorge east of the trench, is apparently not related to the glaciation. It has evidently retreated upstream about 3 miles from the mouth

of the gorge where it is thought to have begun as the effect of an uplift of about 20 feet along the fault. The 3-mile upstream migration of the cascade probably occurred since the Pleistocene (Gibson, 1948, p. 65). As pointed out by Gibson (1948, p. 44), depressions along the fault at Savage Lake also suggest postglacial movements. A Pleistocene age for most of the faulting is evidenced by the well-preserved spur-end facets along the mountain front.

Probable faults.—In addition to those already described several mountain ranges, as suggested by their steep and regular front slopes, were probably elevated by faults along the adjoining basins.

Southeast of Missolula basin (Fig. 20) the steep and regular front of University Mountain suggests the scarp of a fault. The slope rises abruptly from the basin floor to a height of about 800 feet or approximately 4000 feet altitude. Above that height the slope ascends more gradually and is deeply indented by a hanging valley. To the north, across the Clark Fork River, the western side of Mount Jumbo is likewise steep and regular to about the same altitude and above that is also a more gradually rising slope slightly trenched by valleys. The plane formed by the oversteepened lower slopes of both mountains coincides approximately with the dip slope of rocks of the Belt series on the southern part of University Mountain but farther north apparently crosses their structures.

The 4000-foot altitude at which the steep and regular slopes end is also the height of a gravel-veneered plain eroded across the Tertiary "lake beds." Formerly it extended throughout the basin and formed the base level from which the hanging valleys were eroded.

The scarplike lower slopes of University Mountain and Mount Jumbo may have been cut by stream action while the plain at 4000 feet altitude was being dissected, but they probably also represent the footwall of a normal fault that became exposed as the downthrown Tertiary beds were cleared away.

A fault is suggested by the regular course of the mountain front at the north end of Silver Valley (Pl. 1, No. 22), a trenchlike depression east of the Continental Divide north of Helena. The mountain front is the south side of a spur projecting eastward from the Divide. Little Prickly Pear Creek turns into a gorge cut through the spur and passes from the valley alluviam onto bedrock, its current becoming accelerated. East of the gorge the mountain front decreases in height and becomes indefinite, but its projected base line is marked by several springs.

A fault at the foot of Bull Mountain along the east side of Little Whitetail Valley (Pl. 1, No. 35), an arm of the Beaverhead-Jefferson basin, is suggested by the steep, straight, and abruptly rising mountain front and the fact that Tertiary beds in the valley dip toward it.

Toward Libby Valley (Pl. 1, No. 2) on the east the Cabinet Range presents a regular front (Gibson, 1948, Pl. 1, p. 63) with steep spur ends 2000–3000 feet high rising abruptly along a regular course. The fault thus suggested coincides approximately with a dip slope of the rocks of the Belt series. At Granite Creek it is separated by an offset of 2 miles into a longer southern segment and a shorter northern one which is advanced to the east. The two segments trend about N. 25° W.

On the opposite (east) side of the basin a fault dipping inward is suggested by the bold and regular mountain front rising steeply 1000 to 2000 feet from the basin floor north and south of the entrance gorge of the Kootenai River. The supposed fault as traced by the base line of the slope trends about N. 40° W. and is offset about a mile at the gorge; the southern segment is advanced westward.

Other faults are rather strongly suggested by regular mountain fronts rising from the valleys indicated by the numbers on Plate 1 as follows: —Northeast of Lincoln Valley (19); east of Melrose Valley (40); north of upper Madison Valley (49); west of Nicholia Valley (54); west of Medicine Lodge Valley (55); and east of Muddy Creek basin (53).

The Pioneer Mountains (Pl. 1) comprise two north-trending ranges separated by the narrow valley of the Wise River. A probable fault that has downthrown an area of Tertiary "lake beds" within the valley is suggested by the steep and regular mountain front along the east of the Tertiary area.

Some evidence of local downthrows has been

observed back of Drummond at the northern side of the Flint Creek Valley (Pl. 1, No. 24) and along the western side of Deer Lodge Valley (Pl. 1, No. 28) southeast of Gold Creek.

Warping

Mountains.—Some of the ranges and basins appear to be wholly or in part the effects of warping that occurred mostly after the Late Tertiary peneplain had been developed.

Among the mountains (Pl. 1), the Flint Creek Range has the general form of a broad flat dome somewhat elongated north-south. A significant feature is drainage by radial streams. Remnants or representatives of the peneplain take the form of flat-topped or even-crested ridges that reach altitudes of 8000 to 9000 feet in the central part of the dome and, in places along the sides, descend to 6000 feet or less.

The Anaconda Range is a chain of rugged peaks separated by deep precipitous cirques and canyons. Lateral spurs that descend gradually to Philipsburg valley on the north and Big Hole basin on the south are sharp and serrate, but near their outer ends the crests become even and widened with remnants of the peneplain. As reconstructed from these features, the uplift has the form of a wide arch. Its axis, concave to the south, has an average eastward trend.

Other upwarps of the peneplain include the Sapphire Mountains, Bitterroot Mountains (not the Bitterroot Range west of Bitterroot valley), Selish Mountains, Little Belt Mountains, and parts of the Continental Divide between Butte and Helena. Their general summits are undulating maturely dissected surfaces determined by even-crested divides and spurs commonly topped with flat or gently sloping remnants of the peneplain. Their height above neighboring basins ranges from 1000 to 3000 feet.

Basins.—Few of the basins are free of a suspicion of faulting. Among those that appear to be chiefly the effects of downwarping are Flint Creek and Deer Lodge valleys, and Smith River Valley (Pl. 1, No. 31), Philipsburg Valley (Pl. 1, No. 27), and several of the smaller depressions.

Dissection of the Mountains

Old Valley Cycle

During a halt in the post-Miocene uplift of the mountains, rather wide stream valleys were eroded to shallow or moderate depths in the peneplain. After the uplift resumed, many of the streams became diverted and their identities lost. Existing remnants of these abandoned stream valleys form passes or wind gaps in many divides.

Among the remnants of abandoned valleys in the Garnet Range are Stone's Flat and gaps at the heads of Elk Creek and Gambler Gulch (Pardee, 1918b, p. 163–235). Stone's Flat is a rather small and shallow gap, but it contains gold-bearing gravel deposited by its former stream. Quartzite cobbles in the gravel have been softened by decay since they came to place. The other two gaps represent an extension headward of the former Elk Creek.

Passes interpreted as Old Valley remnants occur in most if not all of the other ranges. The larger are half a mile to a mile wide and from a few hundred to nearly 1000 feet deep in the peneplain. Among those on the main travel routes are Pipestone Pass and Homestake Pass (Pl. 5, N) in the Continental Divide east of Butte, and McDonald Pass, Priest Pass (Pl. 2, fig. 3), and Mullan Pass (Pl. 5, O) in the Continental Divide west of Helena.

Several wind gaps, such as Reynolds Pass at the head of Madison Valley and Red Rock Pass at the head of Centennial Valley, are evidently the effects of faulting rather than of erosion although they may once have been occupied by streams.

During uplifts that followed the Old Valley Cycle, several of the larger streams deepened their channels as fast as the surface rose, thus leaving shoulders or other remnants of their Old Valley floors perched above the sides of their lower inner valleys. As represented by these features, the Old Valleys along the Missouri River and Little Prickly Pear Creek where they cross the Belt Mountains below Hilger Valley are about 2 miles wide and 1000 feet or more deep. Cross profiles indicate that Old Valleys of comparable size developed along several other streams: Smith River (Pl. 5, S),

where it crosses the Little Belt Mountains between an intermontane basin (Smith River Valley) and the Great Plains on the north; Sixteenmile Creek (Pl. 5, P) in its course through the Belt Mountains; Gallatin River above Three Forks basin; Rock Creek (Pl. 5, U) in the Sapphire Mountains east of Bitterroot Valley; and the Kootenai River (Pl. 5, R) between Libby and Lake Creek basins. Outstanding examples described by Alden (1924, p. 404, 405, Pls. 16, 17) occur along Sun River and Clark Fork of the Yellowstone River where these streams issue from the mountain province into the Great Plains. At these places the Old Valley floors, represented by rock-cut benches, are as much as 4 miles wide, 1000 to 2000 feet deep in the peneplain, and stand 1000 feet above the present valleys. The Old Valley cycle was contemporaneous with the one in which the Flaxville Plain or No. 1 bench (Alden, 1932, p. 14–18, Pl. 7 A) of the Great Plains was developed.

Present Cycle

The Old Valley cycle was ended by renewed regional differential uplift in which many of the weaker streams became diverted and lost. Most of the more vigorous streams, however, held their courses and excavated the present gorge-like inner valleys.

Dissection of the Basins

In the basins during the Old Valley cycle, surfaces corresponding to No. 1 Bench in the Plains were eroded entirely across the Tertiary "lake beds" and locally onto adjoining areas of the older rocks. In the southern part of the Three Forks basin the gravel-veneered remnant of a plain at 5400 feet altitude that may represent the Old Valley cycle stands 1000 feet above the Madison River near by. It truncates Tertiary "lake beds", its profile descending gradually northward.

In the Present cycle the Old Valley plains were dissected and largely or entirely replaced by a series of lower plains including terraces and the present valley bottoms. In places as they deepened their channels the streams uncovered buried ridges of the older rocks in which they excavated gorges. Striking examples of these are the gorge of the Jefferson River (Atwood, 1916, Pl. XXVII, Figs. 52, 54, p. 717) and three gorges along the Missouri River. One, the Double Horseshoe Gorge of the Missouri River, connects Clarkston and Townsend valleys.

The correlation of the different benches or terrace plains from one valley to another is considered by Alden in a forthcoming paper (In preparation).

Late Stage of the Cenozoic Mountain Building

The structures resulting from the Laramide revolution, exposed in what is now the superficial layer of the earth's crust, were formed by horizontal compression when this layer was deeply buried. Under these conditions the rocks were folded and faulted and displaced by overthrusts. The folding caused a vertical expansion of the mass which in turn elevated the overlying layer and thus may have formed mountains during early Tertiary time. In time this layer was eroded away, and the former subjacent or basement layer became exposed.

These considerations suggest that the mountains formed during late Cenozoic time, in somewhat the same way, might be the effects of renewed horizontal compression in a layer that is now deeply buried. Again the effect of the squeeze would be elevation of the superincumbent layer which, free of horizontal compression but under tensional strains, would tend to crack or split. Moreover, the compressive forces below would tend to shorten the crust. To compensate for this, reverse movements might occur in the superficial layer.

The foregoing is suggested by Molengraaff's interpretation (1913, p. 701) of certain mountains and basins in the East Indian Archipelago as the effects of intense folding in an earlier period closely followed by the Basin and Range or block-faulting type of structural movements. The movement of fault blocks away from the axis of uplift is considered by Fath (1921).

The fault pattern indicates an axis of compression and uplift extending from Yellowstone Park northwestward to the Coeur d'Alene dis-

trict in northern Idaho. With minor exceptions the fault scarps face this line, and the fault blocks are tilted away from it. Although most of the faults in Western Montana are on the northeastern side of this axis, several fault scarps are known in north-central Idaho, and these face it (Anderson, 1934, p. 17–28; Capps, 1940, p. 6, 11, 12) thus tending to balance the pattern.

Local variations in the amount of deep-seated compression may account for differences in the amount of the uplift from place to place. The separation of several of the faults into an echelon segments may be due to drags by parts of the subjacent layer moving at an angle to the compression, an explanation given by Fath (1921, p. 75–84) for en echelon faults in the Mid-Continent field.

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A - Bitterroot range, Bitterroot valley, Sapphire Mountains
- p peneplain
- o old valley
- gr granite
- gn gneiss
- Tlb Tertiary lake beds
- pC Precambrian rocks

B - Madison Valley, Madison Range, and Gallatin Range
- p peneplain
- bas basalt
- bbr basic breccia
- gn gneiss
- pt porphyrite
- Pal Paleozoic
- M Mesozoic

C - Bridger Range
- p peneplain
- o old valley

D - Yellowstone Valley and Beartooth Plateau
- bbr basic breccia
- gn gneiss
- Pal Paleozoic
- M Mesozoic
- Tlb Tertiary "lake beds"

E - Sapphire Mountains, Eastern part
- p peneplain
- pC Precambrian rocks
- Tlb Tertiary "lake beds"

F - Three Forks Basin
- p peneplain
- o old valley (No. 1 bench)
- gn gneiss
- Pal Paleozoic
- M Mesozoic
- Tlb Tertiary "lake beds"

G - Three Forks Basin (west side)
- p peneplain
- o old valley (No. 1 bench)
- gr granite
- gn gneiss
- pC Precambrian rocks
- Pal Paleozoic
- M Mesozoic
- Tlb Tertiary "lake beds"

H - Three Forks basin (east side)
- p peneplain
- o old valley (bench No. 1)
- gn gneiss
- Pal Paleozoic
- M Mesozoic
- Tlb Tertiary "lake beds"

I - Gravelly Range-Madison Range
- p peneplain
- gn gneiss
- Pal Paleozoic
- M Mesozoic
- v volcanics
- Ec Eocene conglomerate
- Tlb Tertiary "lake beds"

K - Continental Divide - Jefferson Range
- p peneplain
- o old valley
- gr granite
- gn gneiss
- PM Paleozoic-Mesozoic
- Tlb Tertiary "lake beds"

L - Deer Lodge Pass - Silverbow basin
- p peneplain
- gr granite
- Tlb Tertiary "lake beds"
- al alluvium

M - Bitterroot-Cabinet-Selish Mountains
- p peneplain
- Qal alluvium

N, O - Continental Divide (longitudinal profiles)
- p peneplain
- o old valley

P - Belt Mountains
- p peneplain
- o old valley

Q - Garnet Range
- p peneplain
- o old valley
- v volcanics

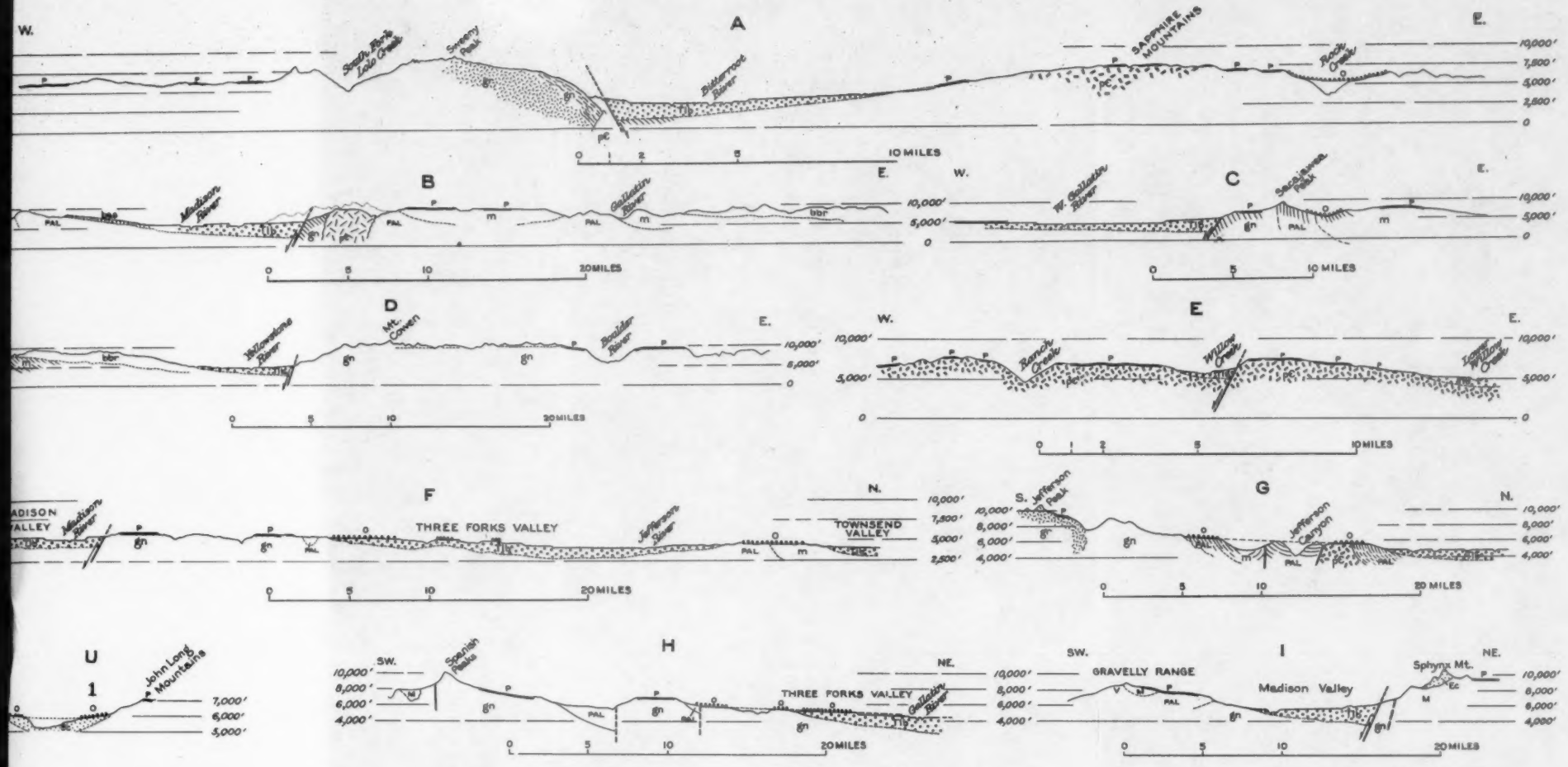
R - Cabinet Range - Purcell Mountains
- p peneplain
- o old valley
- pC Precambrian rocks

S - Little Belt Mountains
- p peneplain
- o - old valley
- pC Precambrian rocks

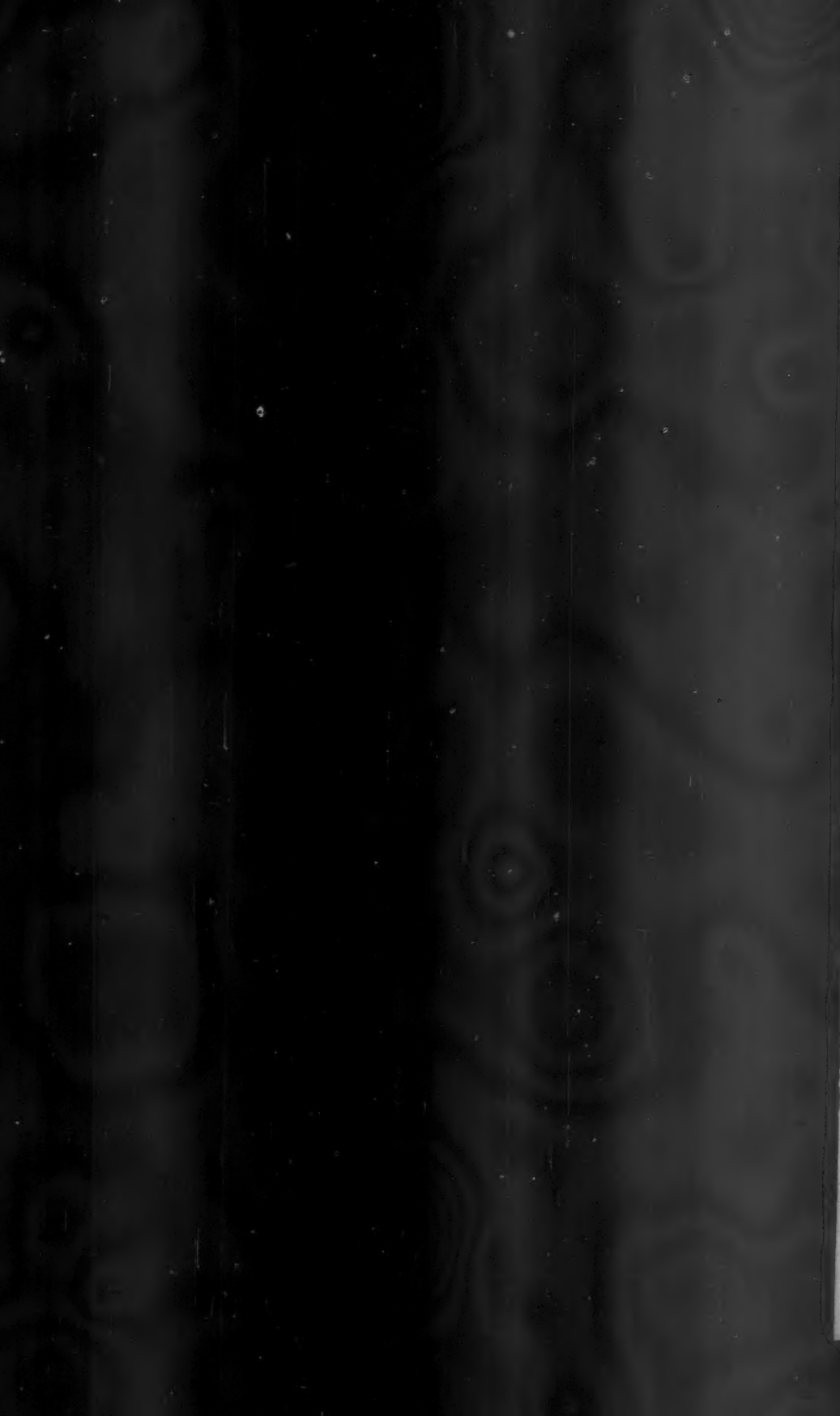
T - Swan Range - Flathead Range

U - Rock Creek Valley
- 1 South of Antelope Creek
- 2 South of Stony Creek
- 3 North of Wyman Creek
- 4 North of Quigley
- p peneplain
- o - old valley
- Ec. Eocene conglomerate

CROSS PROFILES AND SECTIONS



CROSS PROFILES AND SECTIONS



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Short Notes

NORTHWEST OF LAKE TITICACA: CRITICAL REMARKS

By Arnold Heim

The following notes are an answer to the recent book on the Lake Titicaca region by Dr. Norman D. Newell (1949).

In this beautifully illustrated publication, the author maintains his former observations and interpretations (1945; 1946) and rejects my criticism of his preliminary papers (1947; 1948).

It is highly appreciated that my colleague, Doctor Newell, and The Geological Society of America give me the chance to express in English my views on the subject.

When working at the oil field of Pirin on the northwest of Lake Titicaca in 1945, I had the privilege of having at hand the extensive report with the geological maps prepared by Doctor Newell on behalf of the Ministerio de Fomento of Peru. Of particular help was a map, scale 1:10,000, which he had worked out with the help of assistants. Without such fundamental work, it would not have been possible for me to come to definite conclusions on the tectonics of that intricate region of Pusi and the surroundings of the old oil field of Pirin after only a little more than a month's field investigation.

When Doctor Newell returned to Lima in 1947 to continue his work farther north of Lake Titicaca, I invited him to discuss my different views, while he kindly showed me the manuscript prepared for his new book. In this publication, four pages are devoted to rejecting the view brought forward in my publications which appeared since our meeting of 1947. Without changing his previous conceptions, Doctor Newell says: "I confess surprise at his (Heim's) categoric rejection of my conclusions without checking the evidence".

It thus seems necessary to translate into English the eight evidences of my first publication, since they affect the stratigraphy, the tectonics, and the geological history of the whole Titicaca region. The fundamental question is that of the age of Newell's Sipin formation which he considers as basal Cretaceous and therefore constructs huge thrust sheets.

The evidences given in my publication (1947, p. 19–21) are the following, in abbreviated form:

(1) The Sipin formation extends without stratigraphic or tectonic break from the region of Newell's Llocamalla thrust to the overlap on the Devonian, where Newell himself regards it as normally overlapping.

(2) According to Newell (1946, p. 364), essentially horizontal thrust folds found in the hills northwest of Lake Titicaca cover more than 100 square kilometers. According to my observations (Figs. 1, 2), as shown in detail in my sections and in the colored map (scale, 1:6000), the Sipin limestone is *intensely folded* and forms *deep and narrow synclines* with vertical strata. These observations at the surface are proven by well No. 11.

(3) In a dozen places I have examined the exact contact of the Sipin upon other formations considered as younger by Newell. At none of them have I found the slightest indication of thrusting.

(4) Over a large distance the Sipin begins with a regularly stratified calcarous bed 1–3 meters thick. This would hardly be possible if it were at the base of a regional overthrust.

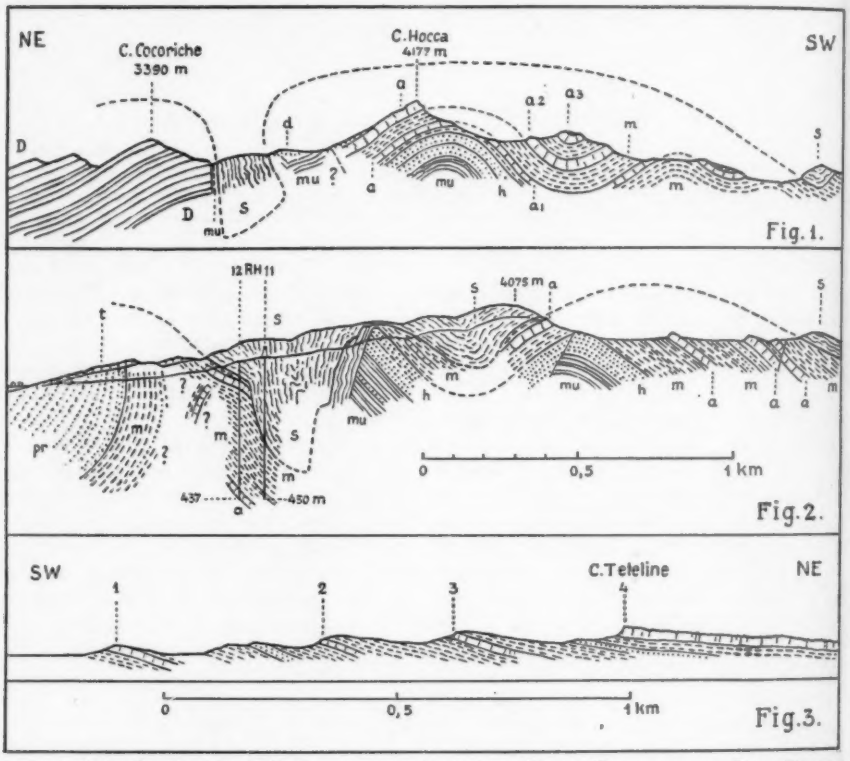
(5) In the region of Pusi, the basalt taken as a Tertiary intrusion belongs to the lower part of the Sipin formation.

(6) Well No. 11 of the oil field of Pirin is not placed on the Moho formation just outside of the supposed Llocamalla thrust, but on vertical Sipin limestone of a deep and

narrow syncline. This surface observation has been checked by the progress of boring. That drilling for about two years was in vain under such conditions is evident.

In their place are narrow and steep Sipin synclines crushed together.

(8) In no place is the Sipin formation found stratigraphically below Cretaceous sediments.



FIGURES 1–2.—CHARACTERISTIC SECTIONS OF THE REGION OF PIRIN, NORTHWEST OF LAGO TITICACA

D, Devonian; mu, Muni formation; h, Huancané sandstone; m, Moho group (red shales and sandstone) including a: Ayavacas limestones Nos. 1–4; s, Sipin formation; t, Travertine, Pliocene; d, debris, talus.

FIGURE 3.—SKETCH OF TETELINE HILL AS IT EMERGES ON THE TITICACA PLAIN 3830 M AT AYAVACAS

Mainly Moho formation (red argillaceous shales with sandstones), interbedded with Ayavacas limestones Nos. 1–4.

(7) In order to give an example of the intense and intricate synclinal folding of the Sipin, I have elaborated the topographical and geological map in colors (1:6000) and the corresponding section (1947, Pl. 1; Fig. 8). It concerns the place found by Newell of the local outcrop of Devonian 2 km west of Pirin, which on Newell's map (Pl. 20) is represented as a triangle bordered by a fault and two overthrusts. According to my observations, the thrusts and the fault line are not confirmed.

In conclusion, I have stressed that the *Llocamalla thrust fold does not exist.* In its place is an *intensely folded unconformity of the Sipin formation*, which overlaps all formations from the Devonian to the middle Cretaceous.

Thus far I had explained my beliefs in 1947.

We now can consider pages 6–9 of Newell's new memoir as far as my observations are concerned.

(1) Doctor Newell emphasizes that in many places the Sipin limestone rests directly with

sedimentary contact upon the Devonian. Certainly it does. But therefrom, in my understanding, it also overlaps the Cretaceous formations.

(2) "In some other places, the Sipin is in contact with the next younger formation with normal stratigraphical contact". According to my observations, the word younger is to be changed to older to make it correct.

(3) As examples of relatively simple structure where the Sipin limestone clearly passes below the higher Mesozoic succession, Newell mentions the following three localities:

(a) Cerro Teteline west of the village of Ayavacas on the road Juliaca-Taraco.

On his geological map, 1:30,000 (Pl. 20), this hill is represented as Moho formation with about four intercalations of Ayavacas limestone, underlain by Huancané sandstone, Muni shale, and Sipin limestone at the base. According to my observations, the hill is essentially made of the red Moho (shales and sandstones) with about four stratigraphic intercalations of Ayavacas limestone. The supposed Sipin at the base is also Ayavacas limestone with remains of fossils (Fig. 3).

(b) "In some other places, the Sipin is in contact with the next younger formation with normal stratigraphical contact". As already stated in my first publication, I have sought in vain a place where the Sipin is stratigraphically overlain by Cretaceous sediments.

(c) In Well RH 1 of 593 m depth at Pirin, Doctor Newell indicates Sipin limestone overlying the Devonian at the base of the Cretaceous. How can this be proven? I regard it as a limestone layer of the Muni formation.

(d) At Cerro Jatun Loma, 2½ km west of Pirin, the sequence as viewed by Newell is overturned, while my detailed map, section No. 2, and Figure 8 show intense synclinal folding of the Sipin with vertical positions and without overturning.

(e) How can "inverted cross-lamination" be distinguished from the normal if the direction of the accumulation is unknown? If inverted over many kilometers as indicated in section B of Plate 21, how can the Huancané sandstone remain over the whole distance in normal thickness and without showing any trace of lamination?

(f) Newell (p. 61) says that the earlier authors Rassmuss (1935) and Cabrera and Peterson (1936) "erroneously supposed that the Ayavacas unit consists of a series of alternating massive limestones and interbedded red shales", and that "generally there is only one massive limestone". According to my observations, the frequent repetitions are generally not caused by thrusting upon each other, but by stratigraphic superposition. Already at the type locality of Ayavacas (Fig. 3) and very clearly at Cerro Hocca (Fig. 1) there are at least three, and probably four or more stratigraphic repetitions of limestones in the red Moho formation. The same fourfold superposition is observed in the region southeast of Pusi (Quebrada Chojela).

(g) "If the Sipin limestone had been deposited over a surface of moderate to high relief, there should be detrital material of the Cretaceous rocks contained in the formation. As a matter of fact, the coarsest Sipin detritus rarely exceeds one millimeter in diameter" (Newell).

It is true that in the Sipin region the Sipin generally begins with nonmetamorphic layers of more or less dense limestone. This fact argues more against far-distance thrusting than for it. Apparently Doctor Newell has not seen the coarse sandstones, breccias, and conglomerates of Quebrada Infierno 2 km west of Pirin, which are several times stratigraphically repeated between strata of typical Sipin limestone (Heim, 1947, map Pl. IV; p. 16). There is to me not the slightest reason to maintain that within the six columnar sections of my Figure 4 five are overturned. The detailed observation clearly showed me that they are in normal position.

The problem of whether the Sipin formation is placed at the bottom of the Cretaceous or on the top of it, and consequently whether the Llocamalla thrust exists or not, is not of local importance only, but exerts its influence far over the Lake Titicaca region. If my view is right, the historic conception must also be partly altered. Years of drilling at the oil field of Pirin have been spent in vain. The last wells, Nos. 11 and 12, have been located by mistake in tectonic interpretation (Fig. 2). Besides the "Llocamalla" thrust sheet, several other thrusts, in my opinion, are doubt-

ful or exaggerated. A great part of the complicated network of overthrusts and faults of the maps of Doctor Newell's book, in my view, will have to be obliterated and converted into unconformities.

In regard to the genesis of Lake Titicaca, Doctor Newell mentions that my observations cover only about 1/600 of the area described by him, and that my "comments on the general geology of Lake Titicaca are not documented and will not be further discussed". He seems not to know of my excursions north of the lake and of a week of travel under the guidance of Dr. F. Ahlfeld around the southern part of it. I may mention that this author of the fundamental *Geologia de Bolivia*, in a letter (Oct. 1947), agrees with my general interpretation in regard to the genesis of Lake Titicaca. The enormous faults designed by Doctor Newell all over the lake are based only on gentle subwater configurations.

In spite of the differences in our points of view, Doctor Newell's book is an enormous step forward. The readers who seriously intend to obtain an impartial view on the discussed problems should consult my publication in Spanish with its numerous figures and plates. Still more desirable would be if an experienced observer in tectonic geology would impartially go over the country again in order to check our observations and deductions.

I know well enough how easy it is in geological field work to be mistaken. I confess that I have been in error more than once. I then have corrected my errors as soon as facts were presented which were opposed to my views. In this particular case, with the best of will, I have found no convincing objections to my presentation. On the contrary, Doctor Newell's valuable book strengthens and supports my views. Let the future judge!

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ATLANTIC BASEMENT ROCKS

By L. Don Leet

In a recent Short Note Ewing, Worzel, Hersey, Press, and Hamilton (1949) reported a velocity of 24,800 ft/sec (7.56 km/sec) for the basement rocks in the Atlantic under 2800 fathoms at 34° N. Lat., 66° 30′ W. Long. They announced that "This was identified with the P_n waves of earthquake seismology attributed to the basaltic layer found below the Mohorovicic discontinuity," and that "The granitic and intermediate layers are thus absent beneath the ocean floor at this point."

Bucher, at the November 1949 meeting in El Paso, stated that "Ewing's conclusions cast doubt on the belief that the floor of the Atlantic Ocean is underlain by a thin 'granitic shell.' Granitic material may be absent over large parts of all oceans."

These conclusions are not justified, even if the data are taken at full face value. Since it was stated that "A first layer was clearly present, but the velocity was not determined," it is obvious that the seismological data are seriously deficient.

It has been recognized generally by seismologists for some years now that the velocity of P_n below the base of the crust in continental areas is 8 km/sec or more. Moreover, the short wave lengths of seismic prospecting frequently resolve local regions of abnormally high velocity which have no observable effect on the longer waves from large blasts and earthquakes. At depths of 7500 to 10,800 feet under Alfalfa County, Oklahoma, the basement has been mapped with a velocity of 24,400 ft/sec (7.4 km/sec) (Leet, 1950), but there has been no suggestion on the basis of this that the granitic layer is missing in North America.

In contrast to the results of Ewing *et al.*, Hill and Swallow (1949) of Cambridge University, in August 1949 found quite different conditions under 1300 fathoms at 53° 50′ N. Lat., 18° 40′ W. Long. There, the sea bed consists of one layer 9000 feet thick (2.75 km) with velocity of compressional waves 2.15 km/sec; another of the same thickness with velocity of 5.0 km/sec; and the basement under these layers with velocity of 6.4 km/sec, which is very close to that now recognized for the granitic layer.

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